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# Designing and Setting up a Process for Assessing Measurement System's Capability

Kiran Namala

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This starred paper submitted by Kiran Namala in partial fulfillment of the requirements for the Degree of Master of Engineering Management at St. Cloud State University is hereby approved by the final evaluation committee.

Chairperson

Dean
School of Graduate Studies

# DESIGNING AND SETTING UP A PROCESS FOR ASSESSING MEASUREMENT SYSTEM'S CAPABILITY

by

Kiran Namala

B.Tech., D.V.R. College of Engineering and Technology, 2005

A Starred Paper

Submitted to the Graduate Faculty

of

St. Cloud State University

in Partial Fulfillment of the Requirements

for the Degree

Master of Engineering Management

St. Cloud, Minnesota

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## ABSTRACT

Measurement Systems Analysis is a methodology applied to measure the amount of variation in the measurement device. The purpose of conducting the MSA study is to quantify measurement error and to reduce the measurement variation to the maximum possible extent. The study is pursued by referring to various quality control books, papers and experts in this area. Potential problems related to the measurement device (if they exist) would be exposed after this study and recommendations would be made in order to achieve a successful quality improvement.

ACKNOWLEDGEMENTS

I express my sincere thanks the committee members for their involvement in my starred paper. I believe that their timely advice and inputs aided me in the successful completion of the paper. I am grateful to Wiman Corporation for allowing me to do this study and providing all the necessary data. I would also like to thank the Mechanical and Manufacturing Engineering Department for providing the resources.

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Chapter 1

# INTRODUCTION

The first step in successful quality improvement or statistical process control program is having good measurement systems. More than often, a measurement system's performance is evaluated by performing a set of designed experiments that quantify the errors in the gage. There are two categories of measurement errors and they are accuracy and precision. Linearity, Stability and Bias are the accuracy errors; Gage Repeatability and Reproducibility (R&R) are accuracy errors. The point of the study is to measure the error in measurement systems. In other words, an MSA study analyzes the variation of measurements of a gage (linearity, bias, and repeatability) and variation of measurement by operators (reproducibility) and variation of measurement due to aging (stability). It is very important in quality control processes as the goal of process control is to eliminate (if possible) or reduce variation in the process and ultimately the products. Studies on measurement variation are not worth the time and money they consume unless they lead to action to reduce process variation and improve process control. To address the problem first we need to measure it precisely, thus the assessment of the gage becomes the priority.

## Statement of the Study

The purpose of this study is to evaluate measurement systems of a plastic sheet film manufacturer in the mid-western United States. Data are retrieved from a set of experiments that are set up on the measurement systems at manufacturing site. This study started in the fall semester, 2005. The researcher observed the plant environment, assisted with the set-up of the experiments and discussed potential problems with the plastic sheet film maker in order to develop the measuring system.

## Need for the Study

This MSA study is specifically designed for the Plastic sheet film manufacturer who purchased a series of thickness measurement equipment and needs to identify the capability of each of the measurement system in order to know which system is best suited depending on the samples being measured.

## Objectives

1. Design and set up a Measurement systems analysis study.
2. Analyze the experimental data.
3. Assess the capability of the measurement system and make recommendations.

## Significance of the Study

Due to heavy competition and customer requirement in the plastic sheet film manufacturing sector, companies need to maintain the high level quality. Customers need a very highly accurate and precise product, thus the range of specification is quite low and sometimes only a target value. It is very tough to manufacture in such a low range. In such situations companies have no room for measurement errors, they need very accurate and precise measuring devices which are very expensive for their line of profit. Besides monitoring the process companies they even need to monitor their gages closely and regularly, being a small/medium sized industry it cannot always invest time and money for measuring devices in getting them calibrated. They need a methodology to monitor the gage themselves. This paper is written to help understand, quantify and measure the variations in the measurement systems.

We have many sources that help us in finding the accuracy and precision of a measuring device, but does that answer the questions like how is gage performing through its range of measurement, over a period of time? Can we measure a measuring device in all its aspects? This paper helps all these answers these questions. A detailed and specific Measurement Systems Analysis study will be developed. This study is planned to identify and thus prevent quality issues that are due to an incapable measurement system. The Measurement systems analysis study is a necessary and efficient quality control tool.

## Limitations of this Study

This study is limited to the researcher's time and the work experience in the plastic sheet manufacturing plant.

## Scope

In the initial efforts to improve quality we measure gage and this paper acts as complete guide in designing and setting up a process for measurement systems analysis for plastic sheet film manufacturer's thickness measuring devices, it answers all questions relating to gage performance and does not go beyond this limit.

## Definitions

Measurement: "The assignment of numbers or values to material things to represent the relations among them with respect to particular properties." This definition was fist given by C. Eisenhart in 1963. The process of assigning the numbers is defined as the measurement process, and the value assigned is defined as the measurement value [1].

Gage: any device used to obtain measurements; frequently used to refer specifically to the devices used on the shop floor; includes go/no-go devices [1].

Measurement system: the collection of operations, procedures, gages and other equipment, software, and personnel used to assign a number to the characteristic being measured; the complete process used to obtain measurements [2].

Master: A standard that is used as a reference in a calibration process. May also be termed as reference or calibration standard [2].

Chapter 2

# LITERATURE REVIEW

Here the concept of measurement systems variation its method of study and its analysis is discussed. It includes a report of findings on the significance of MSA studies on process control.

## Measurement Systems Error

Typically, measurement system errors are classified into two categories: precision and accuracy.

1. Precision: Describes the variation you see when you measure the same part repeatedly with the same device.
2. Accuracy: Accuracy is the difference between the measurement and the part's master or true value.

Every measurement systems, always has one or both of these problems in it. Example, a system may measures samples accurately but not precisely; or a device can be accurate and not precise, which means the measurements have large variation; or a system is neither accurate nor precise (Figure 1).

Measurement Process Variation

The measurement system's variation is characterized by location variation and width vibration.

Location variation. The location variation shows accuracy of the measurement system is. Typically, it is broken into three components: stability, bias, and linearity.

Stability is the total variation in the measurements obtained with a measurement system of the same master or parts when measuring a single characteristic over an extended time period. That is, stability is the change in bias over time ([2]. To determine the Stability enough data should be sampled to cover a wide range of possible variation contributors that are applicable to the process being measured [3].

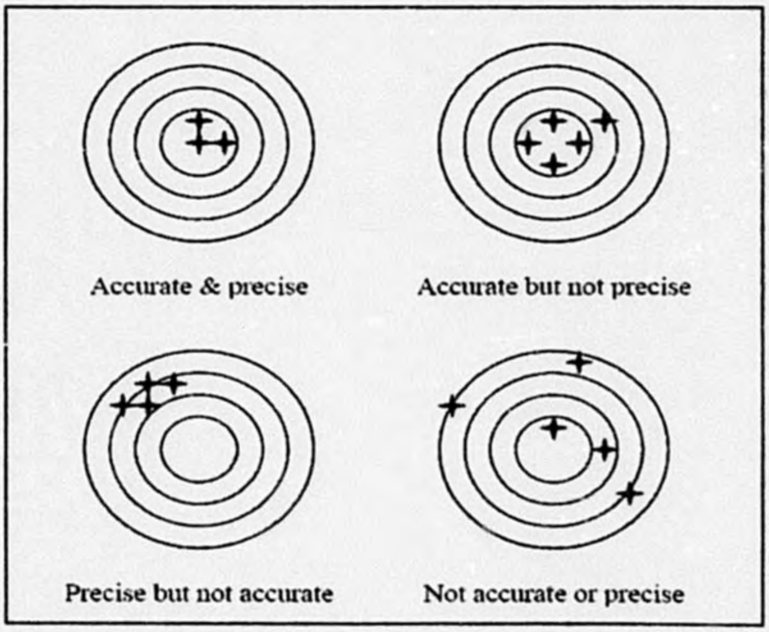



Figure 1: Precision and Accuracy

Instability can be caused by:

1. Worn out systems, normal obsolescence, poor maintenance, distorted gage or part.
2. Calibration, poor quality of instrument (conformance and design), Instrument design robustness.
3. Damaged/ worn master, error in master.
4. Method of measurement–loading, setup, technique, improper use of the setting master.
5. Environmental drift–humidity, vibration, temperature.
6. Violation of an assumption, error in an applied constant.
7. Improper application–position, part size, operator skill, observation error [2].

Bias is the difference between the true value (reference value) and the observed average of measurements on the same characteristic on the same part [2]. It is the measure of the systematic error of the measurement system. Bias is the contribution to the total error consisting of the combined effects of all sources of variation. The variations' contributions to the total error tend to offset predictably and consistently all results of repeated applications of the same measurement process at the measurement time period [2].

Excessive Bias can be resulted from:

1. Worn equipment, instrument, damaged/error master.
2. Calibration, Low quality instrument (conformance, design).

3. Wrong Measuring characteristic, Linearity error.
4. Different measurement method.
5. Environmental drift–humidity, vibration, temperature.
6. Improper use of the setting master [2].

Linearity is the difference of bias throughout the operating range of the equipment [2]. A measurement process can have the capability of measuring small parts but much less accurate when measuring large parts or one end of a long part can be measured more accurately than the other end. It can be considered as a change of bias with respect to size.

If a measurement system has non-linearity, the possible causes can be:

1. Improper instrument calibration at both lower and upper end of the range.
2. Damaged or worn instrument.
3. Imprecise or inaccurate gage for application.
4. Wrong instrument design characteristics.
5. Environmental causes–humidity, vibration, or temperature.

Width Variation

The width variation shows precision of the measurement system is. It is typically broken into two components: Repeatability and Reproducibility.

Repeatability is usually considered as the "with appraiser" variability (the way each operator measures). It is the measurement variation which is obtained with one measurement instrument used by one appraiser several times while measuring the identical characteristic on the same part [2]. Repeatability is a common (random error) variation resulting from successive trials under defined and specific conditions of measurements. The correct term for repeatability is within-system variation when the condition of measurement are defined and fixed (fixed instrument, standard, operator, part, method, and assumptions and environment) [2]. Two common sources of repeatability error are measurement variations due to the position variation of the part and instrument it selves. The range chart is used to show the consistency of the measurement process because both of these variations are represented by the subgroup ranges of repeated measurements.

Besides the two common sources of repeatability errors, other possible errors include:

1. Within-instrument: wear, repair, fixture failure, poor maintenance or quality.
2. Within-standard: class, wear or quality.
3. Within-method: Variation in technique, setup, holding, zeroing, point density, or clamping.
4. Within-part (sample): position, surface finish, form, sample consistency and taper.
5. Within-environment: temperature, humidity, lighting, cleanliness and vibration.
6. Within-appraiser: Position, experience, technique, fell, fatigue or training/ manipulation skill.
7. Wrong gage for the application.
8. Lack of rigidity (gage or part).

9. Violation of an assumption–proper operation or stable.

10. Instrument design or method is not robust and uniform.

11. Application–position, observation error or part size [2].

Reproducibility is defined as the variation in the average of the measurements which are made by different appraisers who use the same measuring instrument when measuring the same characteristic on the same part. This is often true when the manual instruments are influenced by the operators' skill. However, it is not true when the measurement processes (i.e., automated systems) is used where the operator is not a significant source of variation. Because of this reason, reproducibility is considered as the average variation between-conditions or between systems of measurement [4].

Possible sources of reproducibility error in a measurement system include:

1. Between-instruments: average difference using instruments A, B, C, etc., for the same operators, parts and environment.
2. Between-parts: average difference when measuring types of parts A, B, C, etc., using the same instrument, method and operators.
3. Between-methods: average difference caused by changing point densities, zeroing, manual versus automated systems, clamping methods, or holding, etc.
4. Between-standards: average influence of different setting standards in the measurement process.

5. Between-appraisers: average difference between appraisers caused by technique, skill, training and experience. This is recommended study for process qualification and product and a manual instrument.
6. Between-environment: average difference in measurements over time caused by environmental cycles: this is the most common study for highly automated systems in product and process qualification.
7. Instrument design or method is not robust.
8. Assumption violation.
9. Ineffective operator training.
10. Application–position, observation error or part size [2].

Concept of Gage R&R

"Gage refers to any device used for making measurements" [5]. An R&R study analyzes the variation in measurements of a gage (repeatability) and variation in measurements by operators (reproducibility). The Measurement systems analysis studies are a waste of time and money unless they lead to action to reduce process variation and improve process control. "Since you can't address something that cannot be measured precisely, the assessment of the gage becomes an early priority" [5]. "Gage R&R is an estimate of the combined variation of repeatability and reproducibility" [2] (Figure 2). It amounts to the sum of between-system variances and within-system variances.

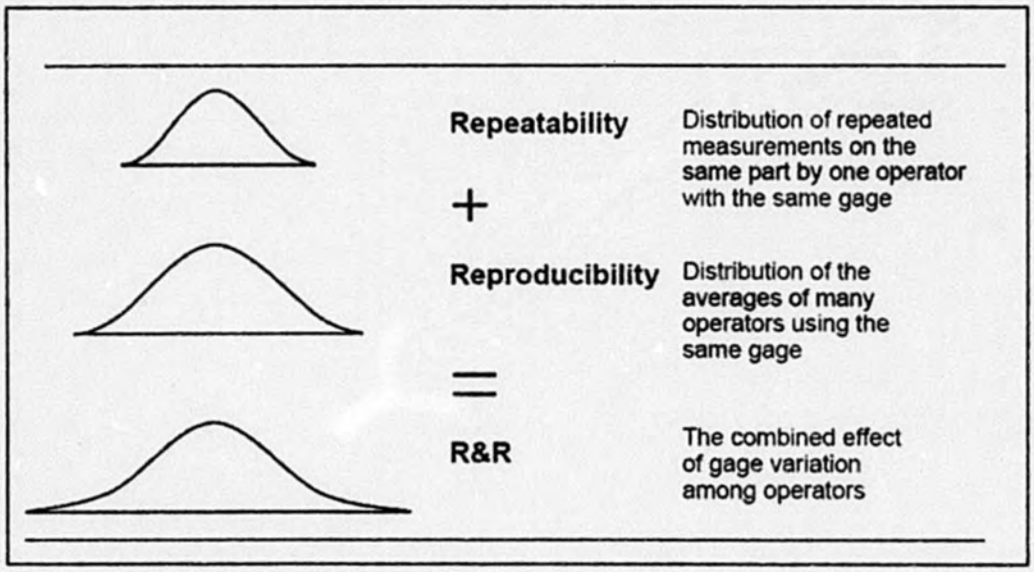



Figure 2: Repeatability, Reproducibility, and R&R [5]

The capacity of a measurement system simply includes the components of:

1. Repeatability and reproducibility (GR&R), including short-term consistency.
2. Uncorrected bias or linearity.

Methods of Gage R&R Study

Gage R&R can be applied to any kind of measurements (attribute or variables, indeterminate or determinate). There are many methods overviewed in the literature that can be used to perform Gage R&R. Below are a few:

1. Average and range method,
2. Analysis of variance (ANOVA) method,
3. Within part variation (WIV) method,
4. Automotive Industry Action Group (AIAG, Southfield, MI) method,

5. Short range method for destructive testing,
6. Short range method for non-destructive testing,
7. Long range method for destructive testing,
8. Long range method for non-destructive testing,
9. The Instantaneous method (one appraiser for equipment variation only) [6].

However, the two most common method types used and supported by statistical software are the ANOVA method (Analysis Of Variance) and the average and range method.

Average and Range Method

The Average and Range method (X and R) provides estimates for variation caused by reproducibility and repeatability. It allows the measurement systems variation into three separate components: part-to-part, repeatability and reproducibility, but not their interaction. The ANOVA method is used to determine this interaction between the gage and appraisers (see figure). Both the Average and Range method and ANOVA method provide information concerning the causes of measurement system or gage error.

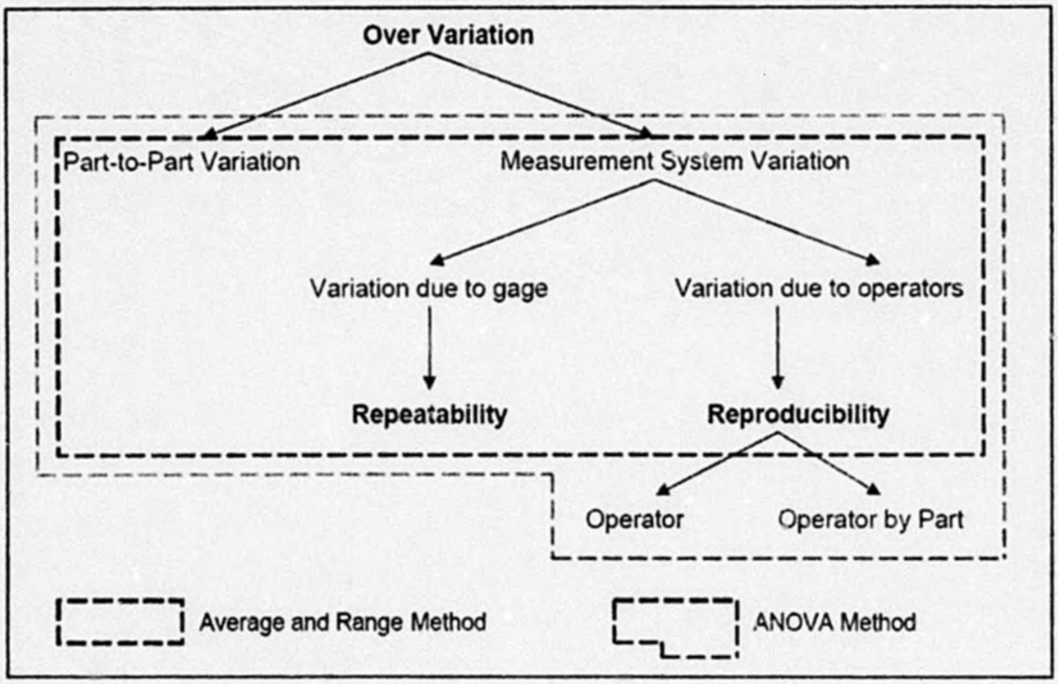



Figure 3: Average and Range Method, ANOVA Method

If reproducibility is large compared to repeatability, then possible causes could be:

1. The appraisers need to be better trained in how to use and read he gage instrument.
2. Calibrations on the gage dial are not correct.
3. A fixture of some sort may be needed to help the appraiser use the gage more consistently.

If repeatability is larger than reproducibly, the reasons may be:

1. The instrument needs to be well maintained.
2. The gage should be redesigned to be more rigid.

3. The location or clamping for gagging needs improvements.
4. There is excessive within-part variation [2].

ANOVA Method

ANOVA is a standard mathematical method for analysis of the measurement error and other sources of variability of data in a measurement systems study [1]. In the analysis of variance, the variation is broken down into four categories: parts, appraisers, interaction between parts and appraisers, and replication error due to the gage.

The advantages of ANOVA techniques over the Average and range methods are that ANOVA has the capability to handle any experimental set-up, estimate the variances with better precision and accuracy, can extract more information from the experimental data. The information includes interaction between parts and appraisers effect.

Evaluation of Results

From a Gage study, %EV (the percent the repeatability or equipment variation), %AV (the percent the appraiser variation), %R&R (the percent the measurement system variation for repeatability and reproducibility) and %PV (the percent the part-part variation) are calculated. Guidelines for acceptance of gage repeatability and reproducibility are:

1. Under 10% error–the measurement system is acceptable(satisfactory),
2. 10% to 30% error–the measurement system may be acceptable depending upon importance of application, cost of repairs or cost of gage, etc.,
3. Over 30% error–measurement system is not satisfactory. It needs improvement. Problems need to be identified and corrected [1].

<u>MSA Process Flow</u>

I. Establish process parameter for the study.

    1. Determine measurement system to be studied.
    2. Establish testing procedure
    3. Determine number of sample parts, number of repeated readings, and number of operators that will be used, choose operators and sample parts.

II. Evaluate measurement system to determine if the system is in statistical control.

    1. Choose sample standards, measure sample standards three to five times.
    2. Plot data on x-bar and R chart.

    Analysis:

    1. Determine if process is in control.
    2. If process is unstable determine and correct the cause.

III. Determine if the measurement system can identify and differentiate between small changes in the given characteristic.

1. Choose a sample standard, measure the sample standard three to five times.
2. Repeat the process 10 to 25 times.
3. Plot data on a R chart

Analysis:

1. The resolution is inadequate if:

   There are only one, two, or three possible values for the range, or

   There are only four possible values for the range when n >= 3.

IV. Determine the variation between the observed measurement and the actual measurement of a part.

1. Choose sample standards, measure sample standards 15 to 25 times using the same measuring device, the same operator, and the same setup.
2. Calculate x-bar and bias:

   Bias = Average – Reference Value
3. Calculate the upper and lower 95% confidence limit (CL).

Analysis:

1. If reference value is within the 95% CL then the bias is insignificant.
2. If reference value is outside the 95% CL then the bias is significant and measurement system must be recalibrated.

Ensure the instrument is accurate, and measurement bias is minimized.

Calibrate instrument any of the manufacturer's instructions.

V. Determine the difference between the obtained value and a reference value using the same instrument over the entire measurement space.

1. Choose three to five sample standards that cover the measurement space.
2. Measure sample standards 15 to 25 times
3. Calculate the average of the readings
4. Calculate bias
5. Plot reference values on x-y graph
6. Calculate slope of the linear regression line
7. Calculate linearity and percent linearity
8. Calculate $R^2$

Analysis:

1. The closer the slope is to zero, the better the instrument.
2. $R^2$ gives indication of how well the "best-fit" line accounts for variability in the x-y graph.

VI. Determine variation in a set of measurement using a single instrument that can be credited to the instrument itself, and to the entire measurement system.

1. Generate random order for operators and parts to complete the run.
2. Repeat process for subsequent runs.
3. Have operators take measurements.

Analysis:

1. Plot data.
2. Run ANOVA (analysis of variance) on data.
3. Calculate total variance.
4. Calculate % Contribution and determine if acceptable.
5. Calculate % Contribution (R&R).
6. Calculate Process to Tolerance ratio (P/T) for repeatability.
7. Determine if P/T is acceptable.

## Chapter 3

## METHODOLOGY

### Subjects

The purpose of this study is to evaluate the capability of the measurement systems that the manufacturing plant has.

### Instrumentation

The data collection sheets were developed by this researcher and adjusted by the plant personnel according to the real measuring environment. Starret (Disk) Micrometer, Digital Indicator and Digital Indicator are considered in this study.

### Methods for Data Collection

To measure the stability a master part has been considered for each of the gage and measured repeatedly 12 times. For Linearity and Bias, three appraisers were used to measure five samples (master parts). Each appraiser had to measure the same sample twelve times for all three gages (Starret/Disk Micrometer, Digital Indicator and Digital indicator). For Repeatability and Reproducibility, three appraisers were used to measure ten samples. Each appraiser had to measure the same part three times for all three gage (Starret/Disk Micrometer, Digital Indicator and Digital indicator).

To minimize the likelihood of misleading results, the following steps were taken.

1. The measurements were made in a random order.
2. The appraisers were unaware of which numbered part was being checked in order to avoid any possible knowledge bias.
3. Each appraiser used the same procedure, including all steps, to obtain the readings.
4. The sample parts were selected from the process and had to represent its entire operating range

Data Analysis

The numerical data that was retrieved by the appraisers has been input to MINITAB15 software for data analysis. MINITAB, a comprehensive statistical and graphical analysis software package and has been providing statistical software solutions for over 25 years. Currently, MINITAB is used by thousands of companies worldwide, including GE, 3M, Ford Motor Company, and the leading Six Sigma consultants.

## Chapter 4

## REPORT OF FINDINGS

All the data has been analyzed through MINTAB 15 software. The capabilities of the three measuring machines (Starret/Disk Micrometer, Digital Indicator and Digital indicator) are to measure all samples. These have been revealed in the data result sheets. Therefore, they could be applied to improve the quality control system in this plant to produce safe and quality products.

### Results

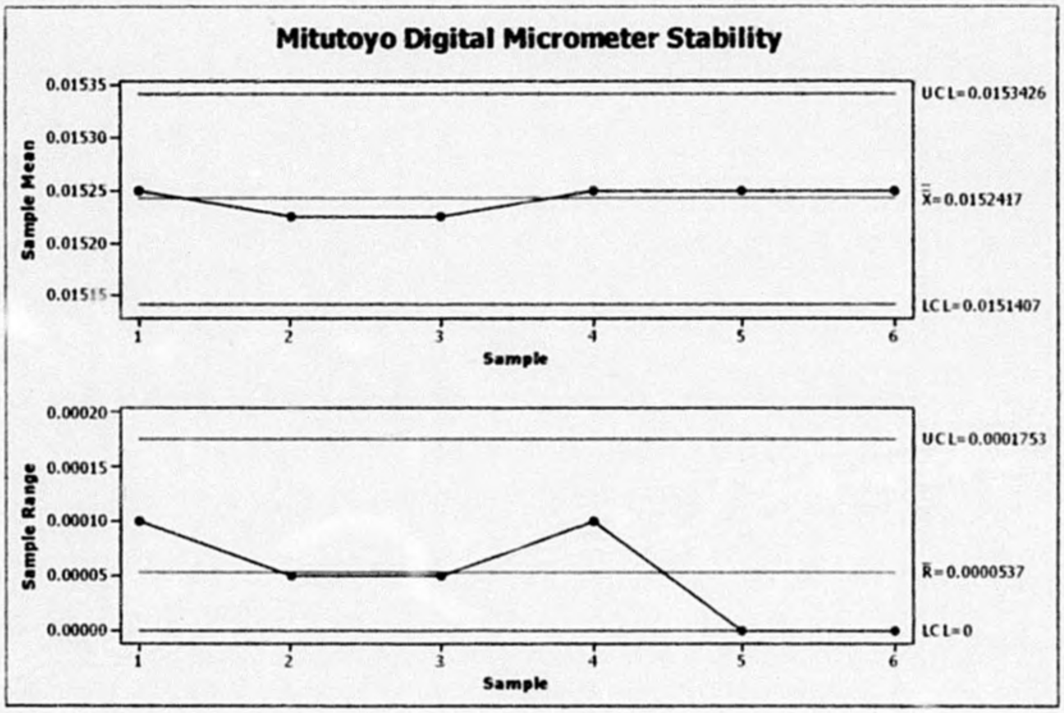
The data collection sheet and the original data results can be reviewed in the appendix at the end of the report.

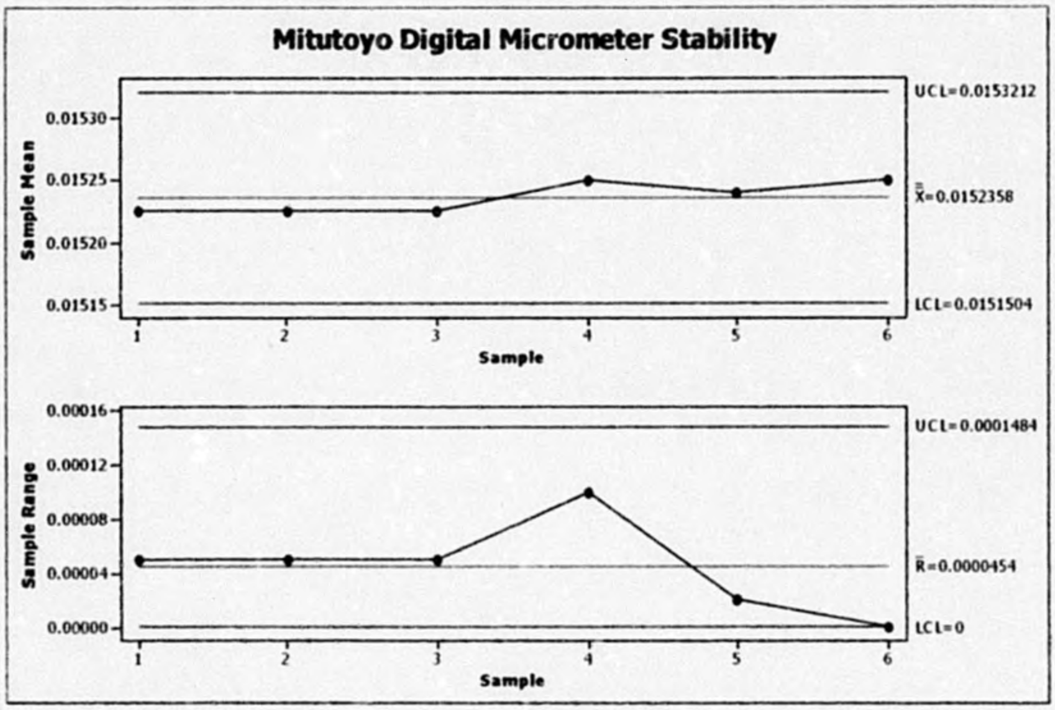
### Summary of Findings

After reviewing the results of this study, it has been determined that the current measurement system is not adequate enough to conduct the necessary daily measuring tasks.

Mitutoyo Digital Micrometer

In this Gage there the difference noticed is negligible it appears that the cause of this variation is Gage R&R which was found in the R&R study, so this gage is stable over the period measured.

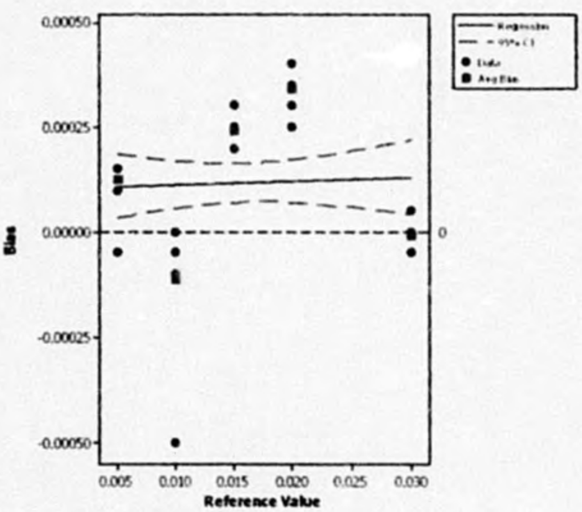





**Gage Linearity and Bias Study for Response**

Gage name: Mitutoyo Digital Micrometer
Date of study:

Reported by:
Tolerance:
Misc:




Gage Linearity

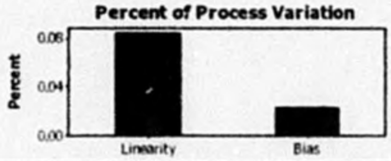
| Predictor | Coef | SE Coef | P |
|---|---|---|---|
| Constant | 0.00010417 | 0.00004903 | 0.038 |
| Slope | 0.000833 | 0.002699 | 0.759 |

| | | | |
|---|---|---|---|
| S | 0.0001798 | R-Sq | 0.2% |
| Linearity | 0.0004370 | % Linearity | 0.1 |

Gage Bias

| Reference | Bias | % Bias | P |
|---|---|---|---|
| Average | 0.0001175 | 0.0 | 0.000 |
| 0.005 | 0.0001250 | 0.0 | 0.000 |
| 0.01 | -0.0001125 | 0.0 | 0.028 |
| 0.015 | 0.0002417 | 0.0 | 0.000 |
| 0.02 | 0.0003417 | 0.1 | 0.000 |
| 0.03 | -0.0000083 | 0.0 | 0.359 |

**Percent of Process Variation**



As we can see bias is less in the range .0 - .015, and for samples around .030. This Gage has more linearity concerns than bias.

**Gage R&R Study - ANOVA Method**

```
Gage R&R for Measurement
Gage name:        Mitutoyo Digital Micrometer
Date of study:
Reported by:
Tolerance:
Misc:
```

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.076456 | 0.0084951 | 1.11115 | 0.403 |
| Operator | 2 | 0.015260 | 0.0076301 | 0.99800 | 0.388 |
| Part * Operator | 18 | 0.137617 | 0.0076454 | 1.00110 | 0.472 → A |
| Repeatability | 60 | 0.458220 | 0.0076370 | | |
| Total | 89 | 0.687553 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.076456 | 0.0084951 | 1.11208 | 0.364 |
| Operator | 2 | 0.015260 | 0.0076301 | 0.99885 | 0.373 |
| Repeatability | 78 | 0.595837 | 0.0076389 | | |
| Total | 89 | 0.687553 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0076389 | 98.77 → B |
| Repeatability | 0.0076389 | 98.77 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000951 | 1.23 → B |
| Total Variation | 0.0077341 | 100.00 |

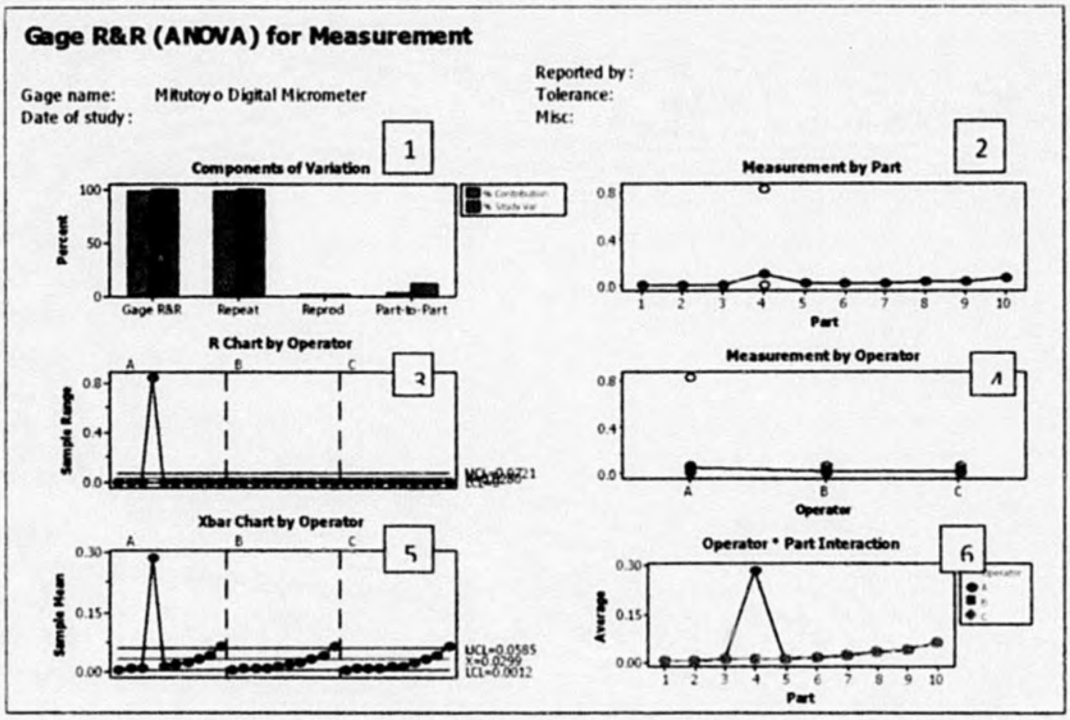
| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0874010 | 0.524406 | 99.38 |
| Repeatability | 0.0874010 | 0.524406 | 99.38 |
| Reproducibility | 0.0000000 | 0.000000 | 0.00 |
| Operator | 0.0000000 | 0.000000 | 0.00 |
| Part-To-Part | 0.0097537 | 0.058522 | 11.09 |
| Total Variation | 0.0879436 | 0.527661 | 100.00 |

Number of Distinct Categories = 1 → C

A—When the p-value for "Operator by Part" is < 0.25, MINITAB fits the full model. In this case, the ANOVA method will be more accurate than the Xbar and R method. If the value is > 0.25, MINITAB fits the model without the interaction and uses the reduced model to define Gage R&R statistics [7].

B—If the percent contribution from Part-Part is larger than that of Total Gage R&R, it tells us that most of the variation is due to differences between parts; very little is due to measurement system error. If the percent contribution from Total gage R&R is larger than that of Part-To-Part, it means that most of the variation is due to the measuring system; very little is due to differences between parts [7].

C—According to AIAG, number "5" represents an adequate measuring system. The lower the number is, the poorer the measurement system would be. A very low number tells us that the measurement system cannot distinguish differences between parts [7].




1. When the p-value for "Operator by Part" is < 0.25, MINITAB fits the full model. In this case, the ANOVA method will be more accurate than the X-bar and R method [7]. If the value is > 0.25, MINITAB fits the model without the interaction and uses the reduced model to define Gage R&R statistics. This graph shows that Part-to-Part variation is very less and most of the variation is due to Gage R&R and specifically repeatability.
2. If the graph represents an erratic line (a non-level line), it tells us there are large differences between Parts. If it is almost a level-line, it tells us there is little difference between parts [7]. The line here is almost a level line indicating less difference between parts, at sample 4 as we can see one

sample is very different from the other samples; here the line passes through mean value of the parts.

3. If the graph represents an erratic line (a non-level line), it indicates that there is large difference between ranges each appraiser is measuring [7], in this case the line is almost flat it indicates that irrespective of the appraiser the measurement range is almost same, sample 4 is an exceptional case.
4. If the graph represents a nearly level line; it tells us there are small differences between operators [7]. If it is a level-line, it tells us there is little difference between operators which is true in this case.
5. If most of the points in the X-bar chart are outside the control limits, indicating the variation is mainly caused by differences between parts. If most of the points in the X-bar are inside the control limits, indicating the variation is mainly due to the measurement system [7].
6. This graph is a visualization of the p-value for Operator*Part. If the value is $< 0.25$, the shape of each line tends to follow the same pattern [7] in this case as all the lines are almost overlapped which indicates the interaction between Part and Operator is negligible.

As we can see a random error in the above analysis, this study is repeated eliminating the random error, below are the results.

Session window output:

## Gage R&R Study - ANOVA Method

Gage R&R for Measurement

```
Gage name:        Mitutoyo Digital Micrometer
Date of study:
Reported by:
Tolerance:
Misc:
```

## Two-Way ANOVA Table With Interaction

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272670 | 0.0030297 | 210844 | 0.000 |
| Operator | 2 | 0.0000002 | 0.0000001 | 7 | 0.005 |
| Part * Operator | 18 | 0.0000003 | 0.0000000 | 0 | 1.000 |
| Repeatability | 60 | 0.0000042 | 0.0000001 | | |
| Total | 89 | 0.0272717 | | | |

Alpha to remove interaction term = 0.25

## Two-Way ANOVA Table Without Interaction

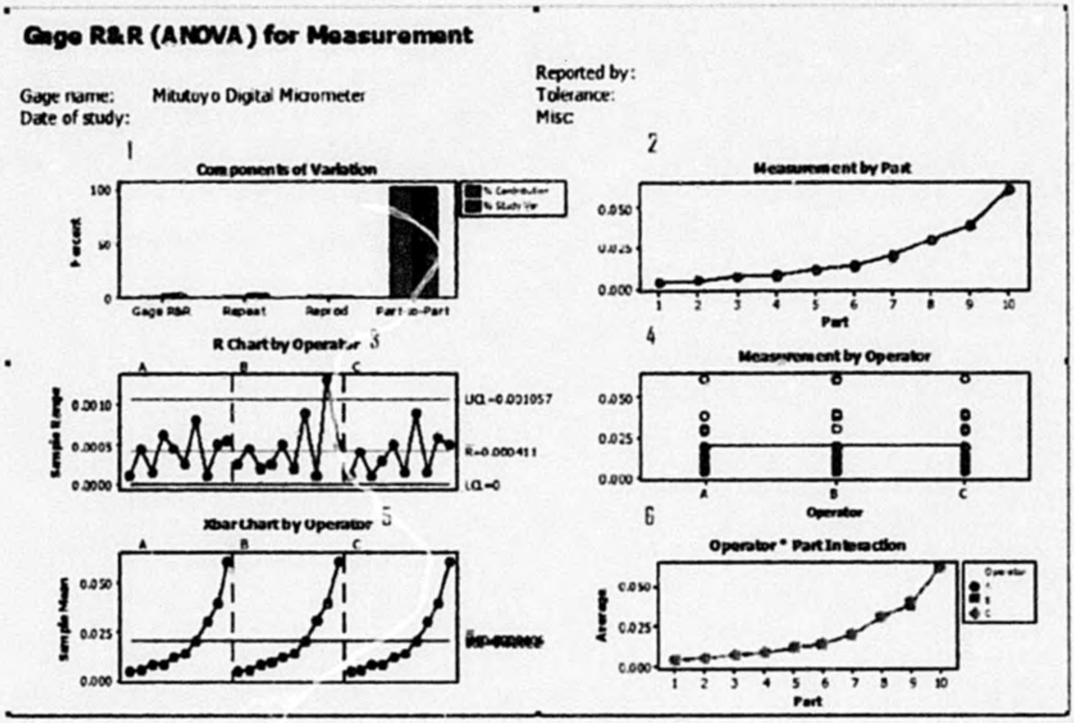
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272670 | 0.0030297 | 53260.9 | 0.000 |
| Operator | 2 | 0.0000002 | 0.0000001 | 1.8 | 0.169 |
| Repeatability | 78 | 0.0000044 | 0.0000001 | | |
| Total | 89 | 0.0272717 | | | |

## Gage R&R

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000001 | 0.02 |
| Repeatability | 0.0000001 | 0.02 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0003366 | 99.98 |
| Total Variation | 0.0003367 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0002417 | 0.001450 | 1.32 |
| Repeatability | 0.0002385 | 0.001431 | 1.30 |
| Reproducibility | 0.0000394 | 0.000236 | 0.21 |
| Operator | 0.0000394 | 0.000236 | 0.21 |
| Part-To-Part | 0.0183473 | 0.110084 | 99.99 |
| Total Variation | 0.0183489 | 0.110093 | 100.00 |

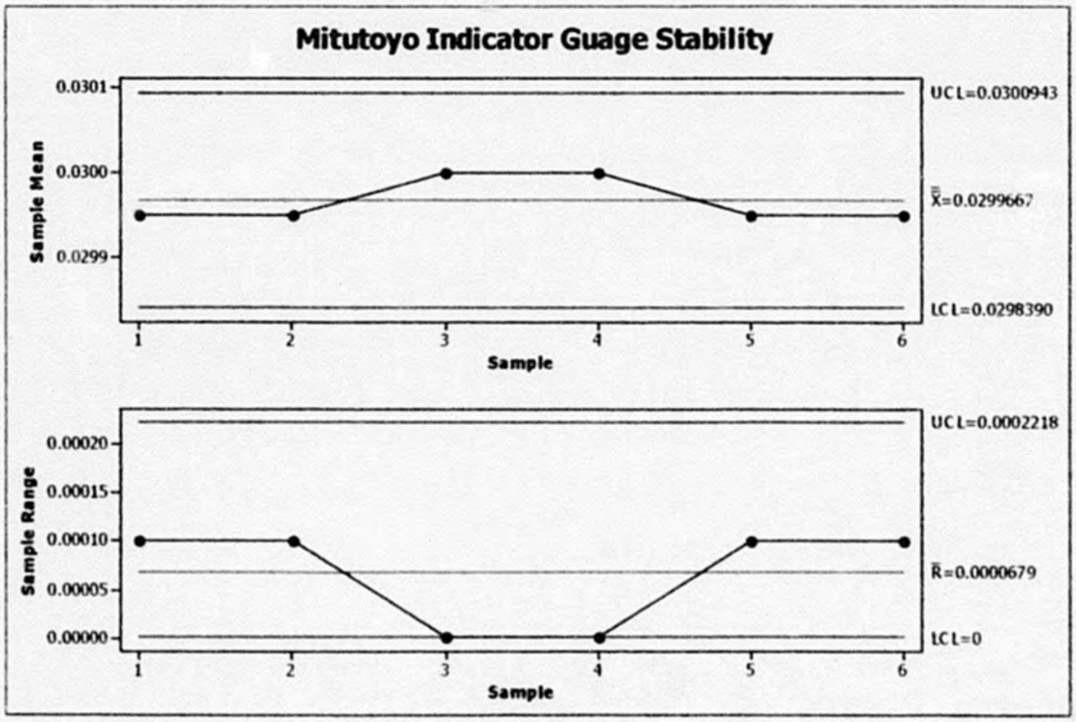
Number of Distinct Categories = 107

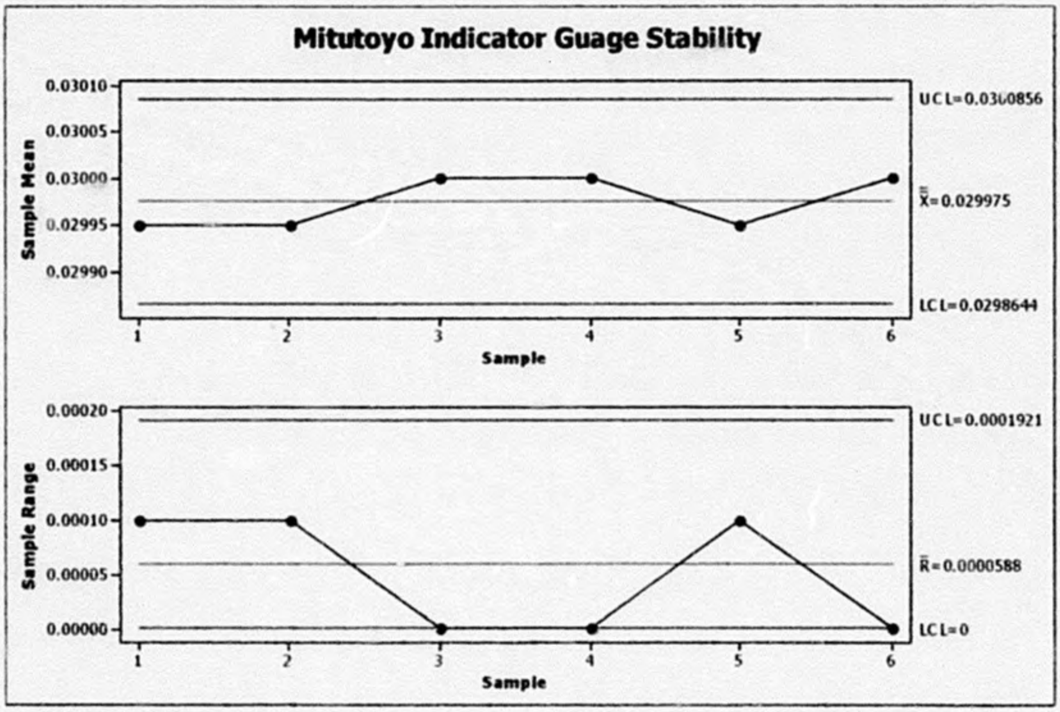



1. This graph shows that Part-to-Part variation is quite high and most of the variation is due to part to part variation only and not due to device's incapability
2. The line here is almost a curved indicating difference between parts, and good potential of gage to identify the difference in them.
3. In this case the line is non-linear indicating good potential of the gage.
4. It is a level line, it tells us there is no difference in the way operators are measuring parts so the reproducibility is good which is anyway indicated in Graph 1.

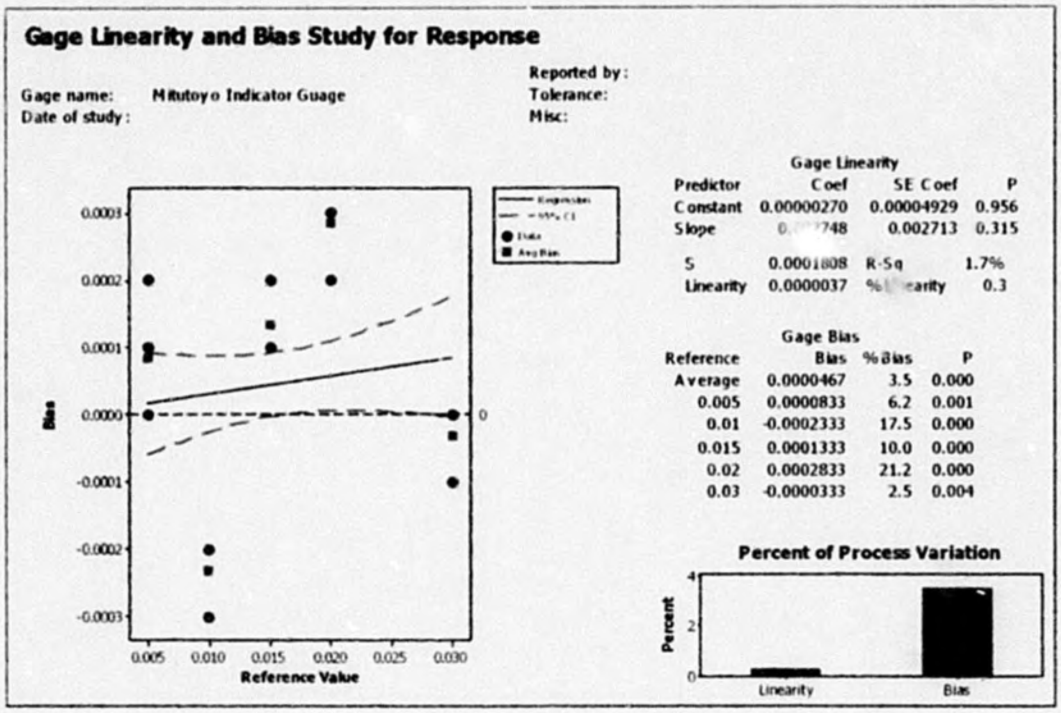
5. Here can notice there is hardly an difference between the way operators are measuring the parts and that the gage is capable of identifying difference in the device.
6. In this graph we can see that all the three lines are overlapped indicating that there is no operator part interaction.

Mitutoyo Indicator Gage






From the above graphs we can see that there is a bit of variation over a period of time, and the cause of this variation is Bias besides aging and wear and tear.




From above graph we can notice that bias is increasing over the range of measurements start from zero, this gage has more Bias concerns.

**Gage R&R Study - ANOVA Method**

Gage R&R for Measurement
Gage name: Mitutoyo Indicator Guage
Date of study:
Reported by:
Tolerance:
Misc:

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 220251 | 0.000 |
| Operator | 2 | 0.0000000 | 0.0000000 | 1 | 0.591 |
| Part * Operator | 18 | 0.0000002 | 0.0000000 | 0 | 0.999 |
| Repeatability | 60 | 0.0000036 | 0.0000001 | | |
| Total | 89 | 0.0272416 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

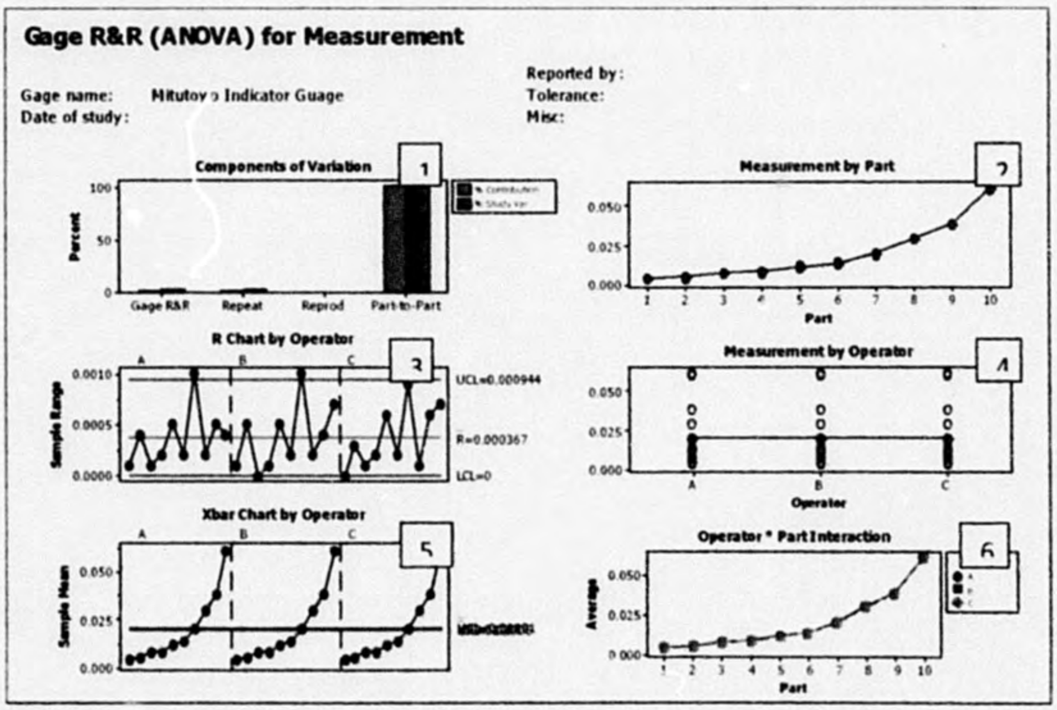
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 61144.9 | 0.000 |
| Operator | 2 | 0.0000000 | 0.0000000 | 0.2 | 0.861 |
| Repeatability | 78 | 0.0000039 | 0.0000000 | | |
| Total | 89 | 0.0272416 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000000 | 0.01 |
| Repeatability | 0.0000000 | 0.01 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0003363 | 99.99 |
| Total Variation | 0.0003363 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0002225 | 0.001335 | 1.21 |
| Repeatability | 0.0002225 | 0.001335 | 1.21 |
| Reproducibility | 0.0000000 | 0.000000 | 0.00 |
| Operator | 0.0000000 | 0.000000 | 0.00 |
| Part-To-Part | 0.0183375 | 0.110025 | 99.99 |
| Total Variation | 0.0183388 | 0.110033 | 100.00 |

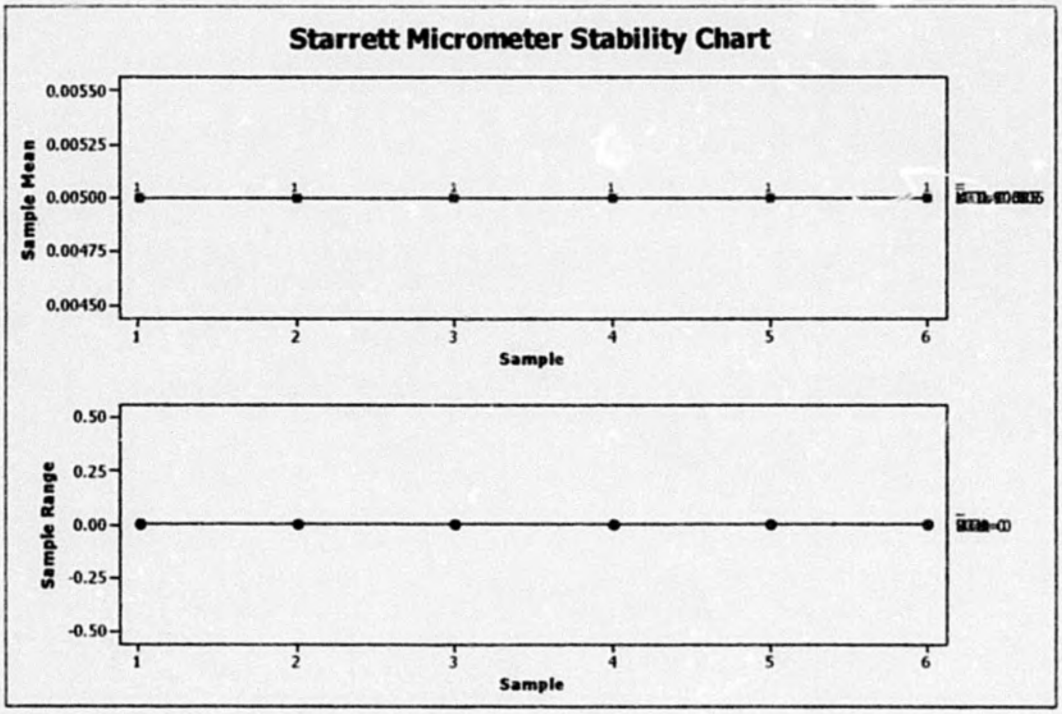
Number of Distinct Categories = 116

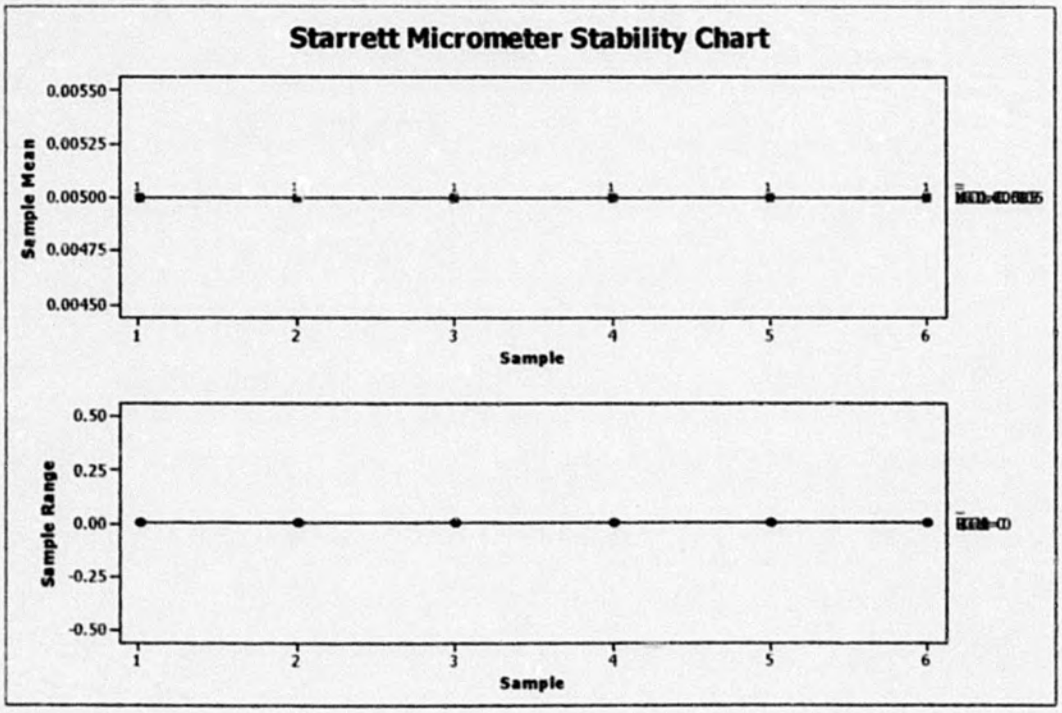


1. In this case also, the ANOVA method will be more accurate than the X-bar and R method. This graph shows that Part-to-Part variation is very high and variation due to Gage R&R is very less.
2. This graph represents an erratic line (a non-level line), indicating that there are large differences between Parts. If it is almost a level-line, it tells us there is little difference between parts.
3. This graph represents an erratic line (a non-level line), indicating that cause of variation is due to part to part variation.
4. This graph represents a nearly level line; indicating that there are very small differences between the way operators are measuring and considerable difference between the parts.
5. Most of the points in the X-bar chart are outside the control limits, indicating the variation is mainly caused by differences between parts and not Gage R&R.
6. This graph is a visualization of the p-value for Operator*Part > 0.25 MINITAB generates a second ANOVA table to omit the interaction term from the model. This graph indicates there is no interaction between operator and part.

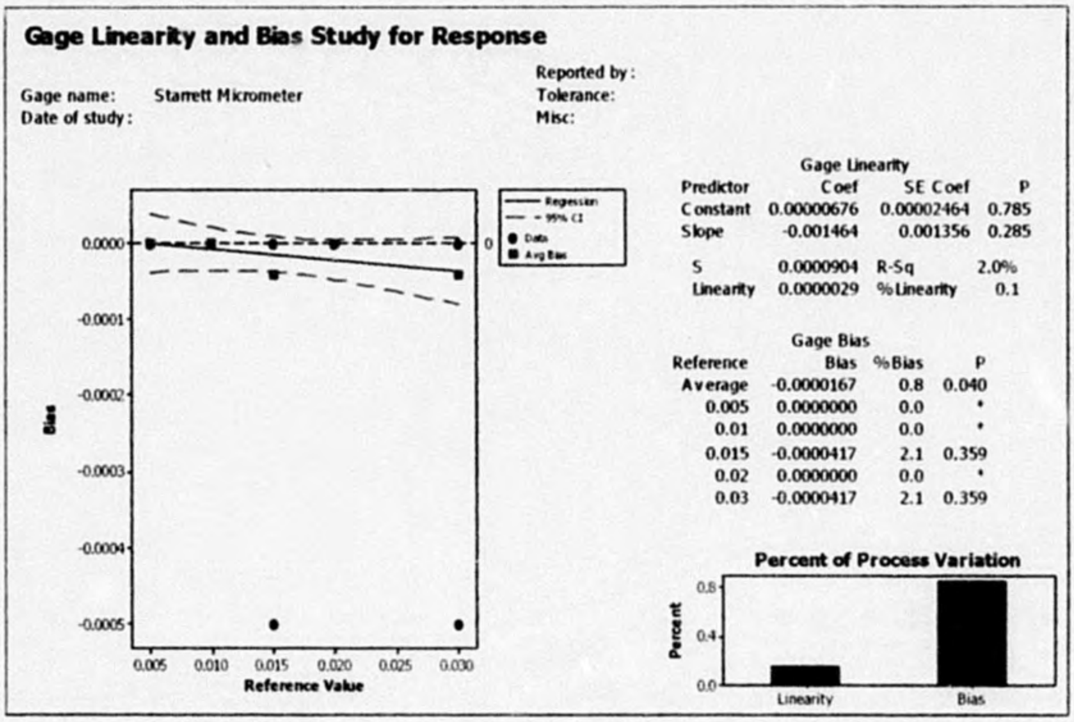
From analysis of above graphs it is clear that main cause of variation in Mitutoyo Indicator is part-to-part variation only and the gage was performing well enough

Starret Micrometer



As this gage has less bias and good precision there is no significant change noticed over time.




In the Linearity and Bias study on Starret Micrometer it is evident that starret micrometer performs best in the range 0-0.010 and for parts around thickness 0.025, it has negligible linearity problem for measuring in around thickness of .015 and .030. This instrument has bias concerns more than linearity.

**Gage R&R Study - ANOVA Method**

```
Gage R&R for Measurement
Gage name:        Starrett Micrometer
Date of study:
Reported by:
Tolerance:
Misc:
```

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 36506.2 | 0.000 |
| Operator | 2 | 0.0000017 | 0.0000009 | 10.3 | 0.001 |
| Part * Operator | 18 | 0.0000015 | 0.0000001 | 1.0 | 0.463 |
| Repeatability | 60 | 0.0000049 | 0.0000001 | | |
| Total | 89 | 0.0272458 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

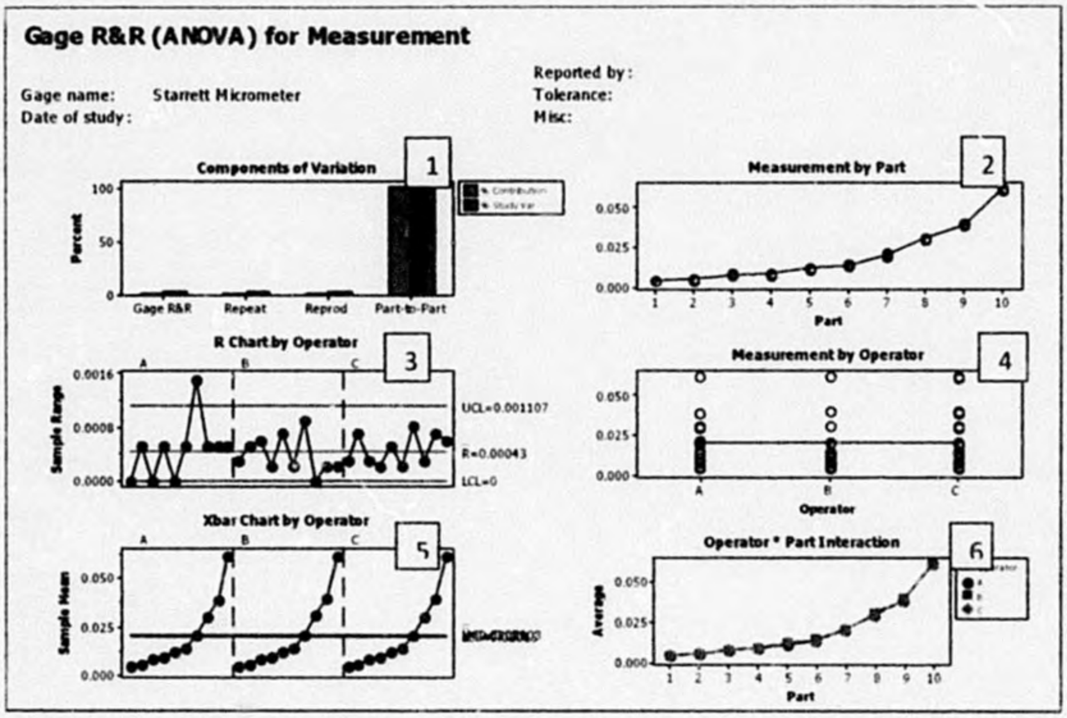
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 36775.8 | 0.000 |
| Operator | 2 | 0.0000017 | 0.0000009 | 10.4 | 0.000 |
| Repeatability | 78 | 0.0000064 | 0.0000001 | | |
| Total | 89 | 0.0272458 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000001 | 0.03 |
| Repeatability | 0.0000001 | 0.02 |
| Reproducibility | 0.0000000 | 0.01 |
| Operator | 0.0000000 | 0.01 |
| Part-To-Part | 0.0003363 | 99.97 |
| Total Variation | 0.0003364 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0003286 | 0.001972 | 1.79 |
| Repeatability | 0.0002869 | 0.001721 | 1.56 |
| Reproducibility | 0.0001603 | 0.000962 | 0.87 |
| Operator | 0.0001603 | 0.000962 | 0.87 |
| Part-To-Part | 0.0183373 | 0.110024 | 99.98 |
| Total Variation | 0.0183403 | 0.110042 | 100.00 |

Number of Distinct Categories = 78




1. Even in this case, the ANOVA method will be more accurate than the X-bar and R method. This graph shows that Part-to-Part variation is very high and variation due to Gage R&R is very less.
2. This graph represents an erratic line (a non-level line), indicating that there are large differences between Parts. If it is almost a level-line, it tells us there is little difference between parts.
3. This graph represents an erratic line (a non-level line), indicating that cause of variation is due to part to part variation.
4. This graph represents a nearly level line; indicating that there are very small differences between the way operators are measuring and considerable difference between the parts.

5. Most of the points in the X-bar chart are outside the control limits, indicating the variation is mainly caused by differences between parts and not Gage R&R.

6. This graph indicates there is no interaction between operator and part.

On the whole we can observe that the Gage is good enough part-to-part variation is cause of observed variation.

Chapter 5

# CONCLUSIONS AND RECOMMENDATIONS

## Statement of the Problem

The study was designed to evaluate the capability of measurement systems for a plastic sheet film manufacturer in the mid-western United States in order to improve the quality of its products.

## Methods and Procedures

The MSA study which thoroughly identifies and quantifies the causes of variation in the measurement systems used. Three measuring devices, Starret Micrometer, Digital Indicator and digital micrometer have been evaluated through the study. Data results were retrieved from MINTAB 15 software and based on these results further analysis was achieved.

## Conclusions

- Digital Micrometer is stable over period of study, has repeatability problems and no reproducibility problems and almost negligible bias concerns, plastic sheet film maker can continue to use this machine if gets the problem solved by calibrating or educating the operator about MSA and problem with this Gage in particular.

- Digital Indicator is quite stable in the period of study, it has bias concerns and is not fit for its intended use, this gage cannot be continued to use though it is able to identify part to part variation to a great extent we cannot consider it without solving bias problem.
- Starret Micrometer is stable during the period of study but has bias problems to a small extent, does not have worth worrying repeatability and reproducibility issues, this gage can be continued to use having the operator educated the bias of this gage.

Recommendations

A thorough understanding of measurement variation and the contribution is essential for operators. It is important to clearly define the problems or issues. Historical flowchart of the measurement systems and processes should be used to discuss the performance capability of the measurement systems itself and its interrelationship to the process.

If in case the major cause of variation is the measurement system itself, it will become necessary to analyze and resolve this issues before working on the process. Sometimes the errors in the measurement system itself are overlooked. Doing that causes loss of resources, time since the focus is made on the process, when the actual problems are due the measurement system.

It is evident from this study that improvement of measurement system is compulsory. As the measuring systems are manual instruments, the study indicates that operator is a significant source of variation, and has trained, qualified operators using these systems.

The changes made in the measurement system and the process should be tested until they reach an appropriate solution and periodically.

# REFERENCES

REFERENCES

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# APPENDIX

**Mitutoto Digital Micrometer – Gage R&R**

| Part | Operator | Measurement |
|---|---|---|
| 1 | A | 0.00455 |
| 1 | A | 0.00455 |
| 1 | A | 0.00465 |
| 2 | A | 0.00535 |
| 2 | A | 0.00570 |
| 2 | A | 0.00525 |
| 3 | A | 0.00850 |
| 3 | A | 0.00835 |
| 3 | A | 0.00835 |
| 4 | A | 0.00900 |
| 4 | A | 0.00890 |
| 4 | A | 0.83800 |
| 5 | A | 0.01230 |
| 5 | A | 0.01255 |
| 5 | A | 0.01210 |
| 6 | A | 0.01450 |
| 6 | A | 0.01435 |
| 6 | A | 0.01460 |
| 7 | A | 0.02005 |
| 7 | A | 0.02085 |
| 7 | A | 0.02085 |
| 8 | A | 0.03045 |
| 8 | A | 0.03050 |
| 8 | A | 0.03055 |
| 9 | A | 0.03910 |
| 9 | A | 0.03925 |
| 9 | A | 0.03960 |
| 10 | A | 0.06210 |
| 10 | A | 0.06175 |
| 10 | A | 0.06155 |
| 1 | B | 0.00450 |
| 1 | B | 0.00465 |
| 1 | B | 0.00475 |
| 2 | B | 0.00560 |
| 2 | B | 0.00580 |
| 2 | B | 0.00535 |
| 3 | B | 0.00860 |

| | | |
|---|---|---|
| 3 | B | 0.00845 |
| 3 | B | 0.00840 |
| 4 | B | 0.00900 |
| 4 | B | 0.00890 |
| 4 | B | 0.00875 |
| 5 | B | 0.01235 |
| 5 | B | 0.01265 |
| 5 | B | 0.01215 |
| 6 | B | 0.01450 |
| 6 | B | 0.01440 |
| 6 | B | 0.01460 |
| 7 | B | 0.02010 |
| 7 | B | 0.02100 |
| 7 | B | 0.02080 |
| 8 | B | 0.03070 |
| 8 | B | 0.03075 |
| 8 | B | 0.03065 |
| 9 | B | 0.03900 |
| 9 | B | 0.03930 |
| 9 | B | 0.04030 |
| 10 | B | 0.06145 |
| 10 | B | 0.06195 |
| 10 | B | 0.06175 |
| 1 | C | 0.00460 |
| 1 | C | 0.00450 |
| 1 | C | 0.00460 |
| 2 | C | 0.00550 |
| 2 | C | 0.00560 |
| 2 | C | 0.00520 |
| 3 | C | 0.00830 |
| 3 | C | 0.00820 |
| 3 | C | 0.00820 |
| 4 | C | 0.00890 |
| 4 | C | 0.00880 |
| 4 | C | 0.00860 |
| 5 | C | 0.01225 |
| 5 | C | 0.01245 |
| 5 | C | 0.01195 |
| 6 | C | 0.01440 |

| | | |
|---|---|---|
| 6 | C | 0.01435 |
| 6 | C | 0.01450 |
| 7 | C | 0.01995 |
| 7 | C | 0.02085 |
| 7 | C | 0.02075 |
| 8 | C | 0.03040 |
| 8 | C | 0.03040 |
| 8 | C | 0.03055 |
| 9 | C | 0.03930 |
| 9 | C | 0.03940 |
| 9 | C | 0.03990 |
| 10 | C | 0.06160 |
| 10 | C | 0.06210 |
| 10 | C | 0.06170 |

**Gage R&R Study - ANOVA Method**

Gage R&R for Measurement
Gage name: Mitutoyo Digital Micrometer
Date of study:
Reported by:
Tolerance:
Misc:

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.076456 | 0.0084951 | 1.11115 | 0.403 |
| Operator | 2 | 0.015260 | 0.0076301 | 0.99800 | 0.388 |
| Part * Operator | 18 | 0.137617 | 0.0076454 | 1.00110 | 0.472 |
| Repeatability | 60 | 0.458220 | 0.0076370 | | |
| Total | 89 | 0.687553 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

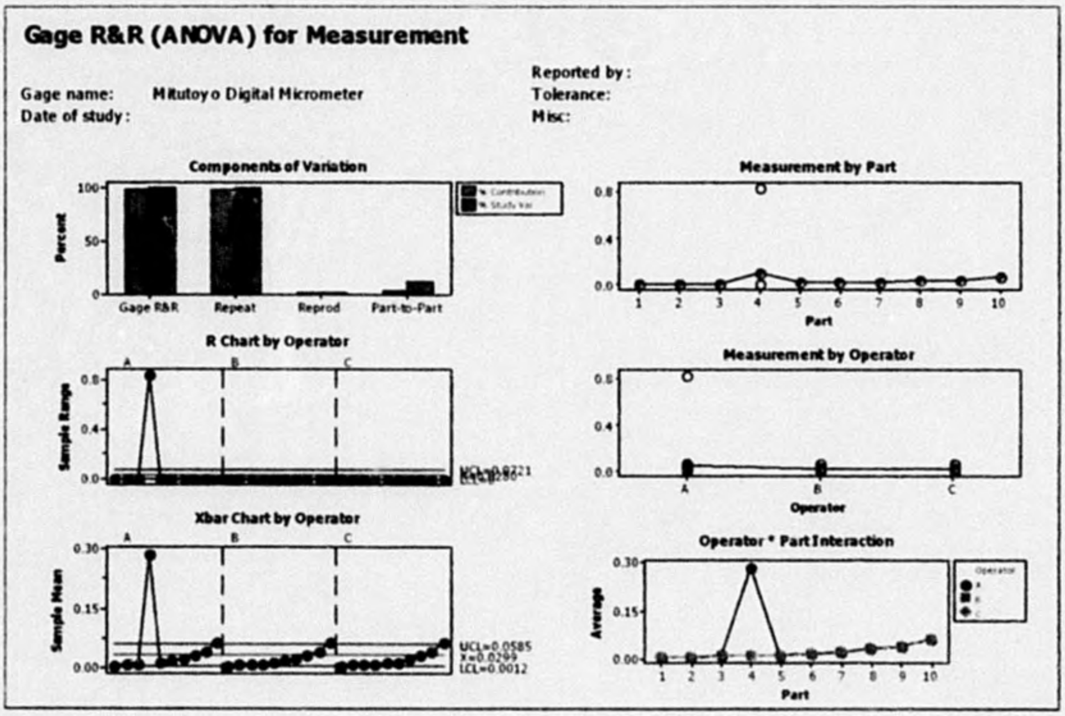
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.076456 | 0.0084951 | 1.11208 | 0.364 |
| Operator | 2 | 0.015260 | 0.0076301 | 0.99885 | 0.373 |
| Repeatability | 78 | 0.595837 | 0.0076389 | | |
| Total | 89 | 0.687553 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0076389 | 98.77 |
| Repeatability | 0.0076389 | 98.77 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000951 | 1.23 |
| Total Variation | 0.0077341 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0874010 | 0.524406 | 99.38 |
| Repeatability | 0.0874010 | 0.524406 | 99.38 |
| Reproducibility | 0.0000000 | 0.000000 | 0.00 |
| Operator | 0.0000000 | 0.000000 | 0.00 |
| Part-To-Part | 0.0097537 | 0.058522 | 11.09 |
| Total Variation | 0.0879436 | 0.527661 | 100.00 |

Number of Distinct Categories = 1




Session window output:

## Gage R&R Study - ANOVA Method

```
Gage R&R for Measurement

Gage name:        Mitutoyo Digital Micrometer
Date of study:
Reported by:
Tolerance:
Misc:
```

### Two-Way ANOVA Table With Interaction

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272670 | 0.0030297 | 210844 | 0.000 |
| Operator | 2 | 0.0000002 | 0.0000001 | 7 | 0.005 |
| Part * Operator | 18 | 0.0000003 | 0.0000000 | 0 | 1.000 |
| Repeatability | 60 | 0.0000042 | 0.0000001 | | |
| Total | 89 | 0.0272717 | | | |

Alpha to remove interaction term = 0.25

### Two-Way ANOVA Table Without Interaction

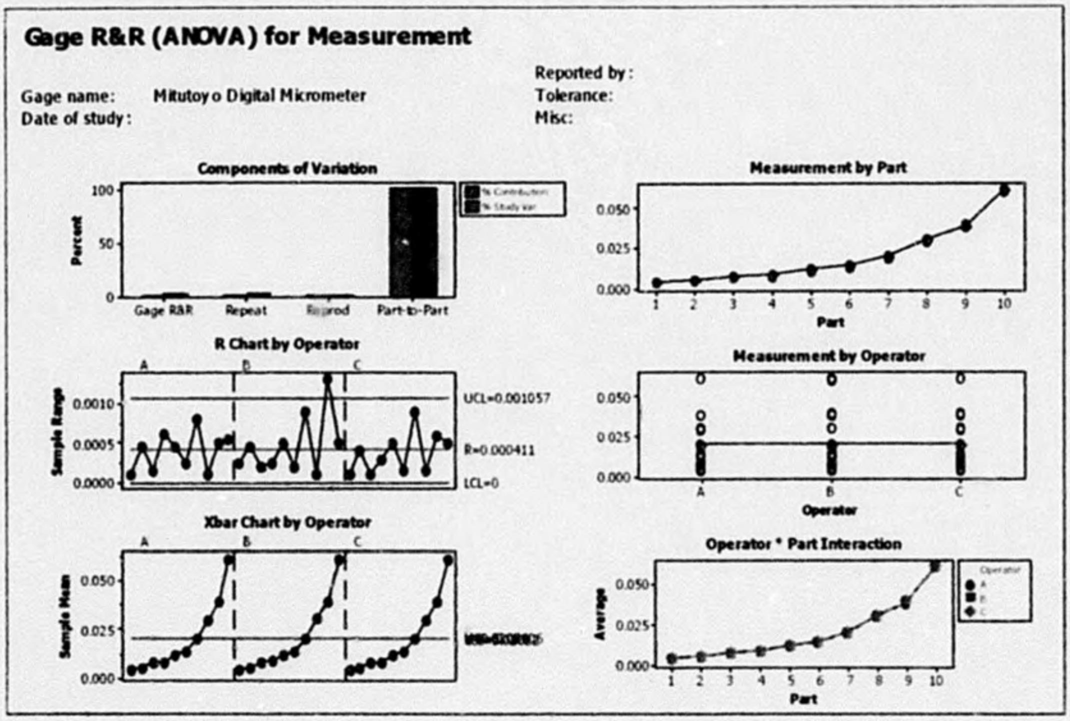
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272670 | 0.0030297 | 53260.9 | 0.000 |
| Operator | 2 | 0.0000002 | 0.0000001 | 1.8 | 0.169 |
| Repeatability | 78 | 0.0000044 | 0.0000001 | | |
| Total | 89 | 0.0272717 | | | |

### Gage R&R

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000001 | 0.02 |
| Repeatability | 0.0000001 | 0.02 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0003366 | 99.98 |
| Total Variation | 0.0003367 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0002417 | 0.001450 | 1.32 |
| Repeatability | 0.0002385 | 0.001431 | 1.30 |
| Reproducibility | 0.0000394 | 0.000236 | 0.21 |
| Operator | 0.0000394 | 0.000236 | 0.21 |
| Part-To-Part | 0.0183473 | 0.110084 | 99.99 |
| Total Variation | 0.0183489 | 0.110093 | 100.00 |

Number of Distinct Categories = 107




## Mitutoyo Indicator gage – Gage R&R

| Part | Operator | Measurement |
|---|---|---|
| 1 | A | 0.0044 |
| 1 | A | 0.0044 |
| 1 | A | 0.0045 |
| 2 | A | 0.0053 |
| 2 | A | 0.0055 |
| 2 | A | 0.0051 |
| 3 | A | 0.0083 |
| 3 | A | 0.0082 |
| 3 | A | 0.0082 |
| 4 | A | 0.0088 |
| 4 | A | 0.0087 |
| 4 | A | 0.0086 |
| 5 | A | 0.0120 |
| 5 | A | 0.0123 |
| 5 | A | 0.0118 |
| 6 | A | 0.0143 |
| 6 | A | 0.0142 |
| 6 | A | 0.0144 |
| 7 | A | 0.0198 |
| 7 | A | 0.0208 |
| 7 | A | 0.0207 |
| 8 | A | 0.0304 |
| 8 | A | 0.0303 |
| 8 | A | 0.0305 |
| 9 | A | 0.0387 |
| 9 | A | 0.0388 |
| 9 | A | 0.0392 |

| | | |
|---|---|---|
| 10 | A | 0.0613 |
| 10 | A | 0.0617 |
| 10 | A | 0.0614 |
| 1 | B | 0.0044 |
| 1 | B | 0.0043 |
| 1 | B | 0.0044 |
| 2 | B | 0.0054 |
| 2 | B | 0.0055 |
| 2 | B | 0.0050 |
| 3 | B | 0.0082 |
| 3 | B | 0.0082 |
| 3 | B | 0.0082 |
| 4 | B | 0.0087 |
| 4 | B | 0.0087 |
| 4 | B | 0.0086 |
| 5 | B | 0.0119 |
| 5 | B | 0.0123 |
| 5 | B | 0.0118 |
| 6 | B | 0.0143 |
| 6 | B | 0.0142 |
| 6 | B | 0.0144 |
| 7 | B | 0.0198 |
| 7 | B | 0.0208 |
| 7 | B | 0.0207 |
| 8 | B | 0.0304 |
| 8 | B | 0.0303 |
| 8 | B | 0.0305 |
| 9 | B | 0.0388 |
| 9 | B | 0.0389 |
| 9 | B | 0.0392 |
| 10 | B | 0.0614 |
| 10 | B | 0.0621 |
| 10 | B | 0.0619 |
| 1 | C | 0.0044 |
| 1 | C | 0.0044 |
| 1 | C | 0.0044 |
| 2 | C | 0.0053 |
| 2 | C | 0.0054 |
| 2 | C | 0.0051 |
| 3 | C | 0.0083 |
| 3 | C | 0.0082 |
| 3 | C | 0.0082 |
| 4 | C | 0.0088 |
| 4 | C | 0.0087 |
| 4 | C | 0.0086 |
| 5 | C | 0.0119 |
| 5 | C | 0.0123 |
| 5 | C | 0.0117 |
| 6 | C | 0.0143 |
| 6 | C | 0.0142 |
| 6 | C | 0.0144 |
| 7 | C | 0.0199 |
| 7 | C | 0.0208 |
| 7 | C | 0.0207 |
| 8 | C | 0.0304 |
| 8 | C | 0.0303 |
| 8 | C | 0.0304 |
| 9 | C | 0.0387 |
| 9 | C | 0.0390 |
| 9 | C | 0.0393 |

| | | |
|---|---|---|
| 10 | C | 0.0615 |
| 10 | C | 0.0622 |
| 10 | C | 0.0617 |

**Gage R&R Study - ANOVA Method**

Gage R&R for Measurement
Gage name: Mitutoyo Indicator Guage
Date of study:
Reported by:
Tolerance:
Misc:

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 220251 | 0.000 |
| Operator | 2 | 0.0000000 | 0.0000000 | 1 | 0.591 |
| Part * Operator | 18 | 0.0000002 | 0.0000000 | 0 | 0.999 |
| Repeatability | 60 | 0.0000036 | 0.0000001 | | |
| Total | 89 | 0.0272416 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

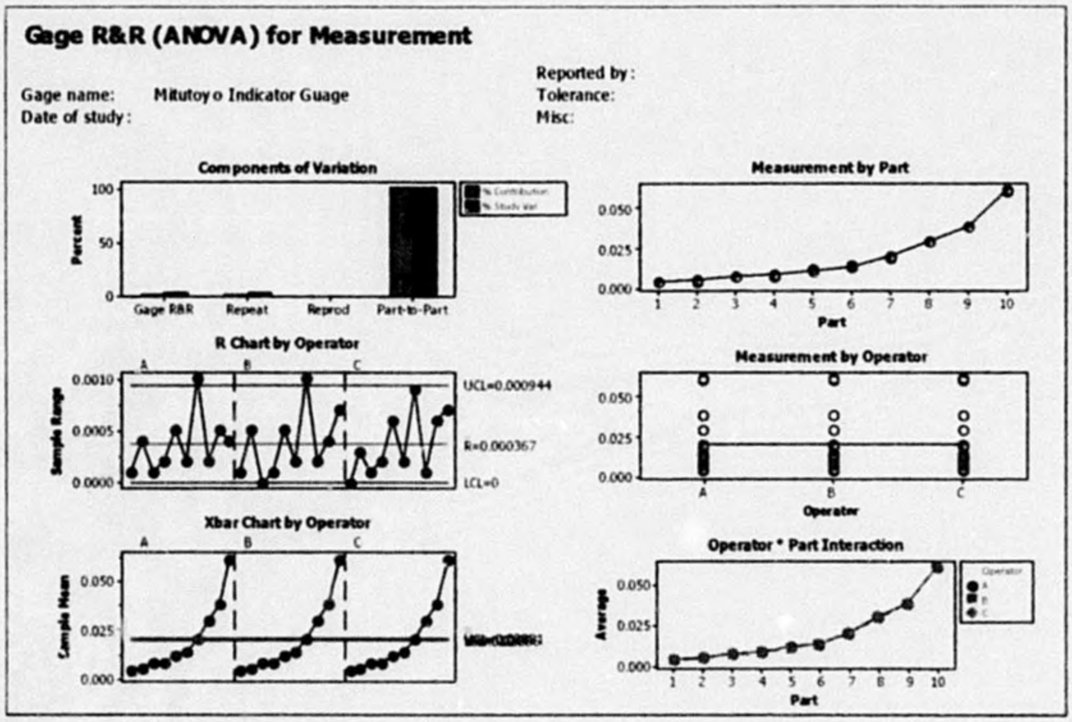
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 61144.9 | 0.000 |
| Operator | 2 | 0.0000000 | 0.0000000 | 0.2 | 0.861 |
| Repeatability | 78 | 0.0000039 | 0.0000000 | | |
| Total | 89 | 0.0272416 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000000 | 0.01 |
| Repeatability | 0.0000000 | 0.01 |
| Reproducibility | 0.0000000 | 0.00 |
| Operator | 0.0000000 | 0.00 |
| Part-To-Part | 0.0003363 | 99.99 |
| Total Variation | 0.0003363 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0002225 | 0.001335 | 1.21 |
| Repeatability | 0.0002225 | 0.001335 | 1.21 |
| Reproducibility | 0.0000000 | 0.000000 | 0.00 |
| Operator | 0.0000000 | 0.000000 | 0.00 |
| Part-To-Part | 0.0183375 | 0.110025 | 99.99 |
| Total Variation | 0.0183388 | 0.110033 | 100.00 |

Number of Distinct Categories = 116




Starret Micrometer – Gage R&R

| Part | Operator | Measurement |
|---|---|---|
| 1 | A | 0.0045 |
| 1 | A | 0.0045 |
| 1 | A | 0.0045 |
| 2 | A | 0.0055 |
| 2 | A | 0.0055 |
| 2 | A | 0.0050 |
| 3 | A | 0.0080 |
| 3 | A | 0.0080 |
| 3 | A | 0.0080 |
| 4 | A | 0.0090 |
| 4 | A | 0.0090 |
| 4 | A | 0.0085 |
| 5 | A | 0.0120 |
| 5 | A | 0.0120 |
| 5 | A | 0.0120 |
| 6 | A | 0.0140 |
| 6 | A | 0.0140 |
| 6 | A | 0.0145 |
| 7 | A | 0.0200 |
| 7 | A | 0.0210 |
| 7 | A | 0.0215 |
| 8 | A | 0.0300 |
| 8 | A | 0.0300 |
| 8 | A | 0.0305 |
| 9 | A | 0.0390 |
| 9 | A | 0.0390 |
| 9 | A | 0.0395 |
| 10 | A | 0.0615 |

| | | |
|---|---|---|
| 10 | A | 0.0620 |
| 10 | A | 0.0620 |
| 1 | B | 0.0048 |
| 1 | B | 0.0045 |
| 1 | B | 0.0048 |
| 2 | B | 0.0058 |
| 2 | B | 0.0058 |
| 2 | B | 0.0053 |
| 3 | B | 0.0088 |
| 3 | B | 0.0082 |
| 3 | B | 0.0083 |
| 4 | B | 0.0091 |
| 4 | B | 0.0090 |
| 4 | B | 0.0089 |
| 5 | B | 0.0125 |
| 5 | B | 0.0127 |
| 5 | B | 0.0120 |
| 6 | B | 0.0145 |
| 6 | B | 0.0143 |
| 6 | B | 0.0145 |
| 7 | B | 0.0201 |
| 7 | B | 0.0210 |
| 7 | B | 0.0209 |
| 8 | B | 0.0308 |
| 8 | B | 0.0308 |
| 8 | B | 0.0308 |
| 9 | B | 0.0398 |
| 9 | B | 0.0400 |
| 9 | B | 0.0399 |
| 10 | B | 0.0618 |
| 10 | B | 0.0620 |
| 10 | B | 0.0618 |
| 1 | C | 0.0045 |
| 1 | C | 0.0043 |
| 1 | C | 0.0046 |
| 2 | C | 0.0058 |
| 2 | C | 0.0053 |
| 2 | C | 0.0051 |
| 3 | C | 0.0084 |
| 3 | C | 0.0082 |
| 3 | C | 0.0081 |
| 4 | C | 0.0090 |
| 4 | C | 0.0089 |
| 4 | C | 0.0088 |
| 5 | C | 0.0121 |
| 5 | C | 0.0125 |
| 5 | C | 0.0120 |
| 6 | C | 0.0143 |
| 6 | C | 0.0142 |
| 6 | C | 0.0144 |
| 7 | C | 0.0200 |
| 7 | C | 0.0208 |
| 7 | C | 0.0207 |
| 8 | C | 0.0303 |
| 8 | C | 0.0302 |
| 8 | C | 0.0305 |
| 9 | C | 0.0392 |
| 9 | C | 0.0391 |
| 9 | C | 0.0398 |
| 10 | C | 0.0611 |

| | | |
|---|---|---|
| **10** | **C** | **0.0611** |
| **10** | **C** | **0.0617** |

**Gage R&R Study - ANOVA Method**

Gage R&R for Measurement
Gage name: Starrett Micrometer
Date of study:
Reported by:
Tolerance:
Misc:

**Two-Way ANOVA Table With Interaction**

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 36506.2 | 0.000 |
| Operator | 2 | 0.0000017 | 0.0000009 | 10.3 | 0.001 |
| Part * Operator | 18 | 0.0000015 | 0.0000001 | 1.0 | 0.463 |
| Repeatability | 60 | 0.0000049 | 0.0000001 | | |
| Total | 89 | 0.0272458 | | | |

Alpha to remove interaction term = 0.25

**Two-Way ANOVA Table Without Interaction**

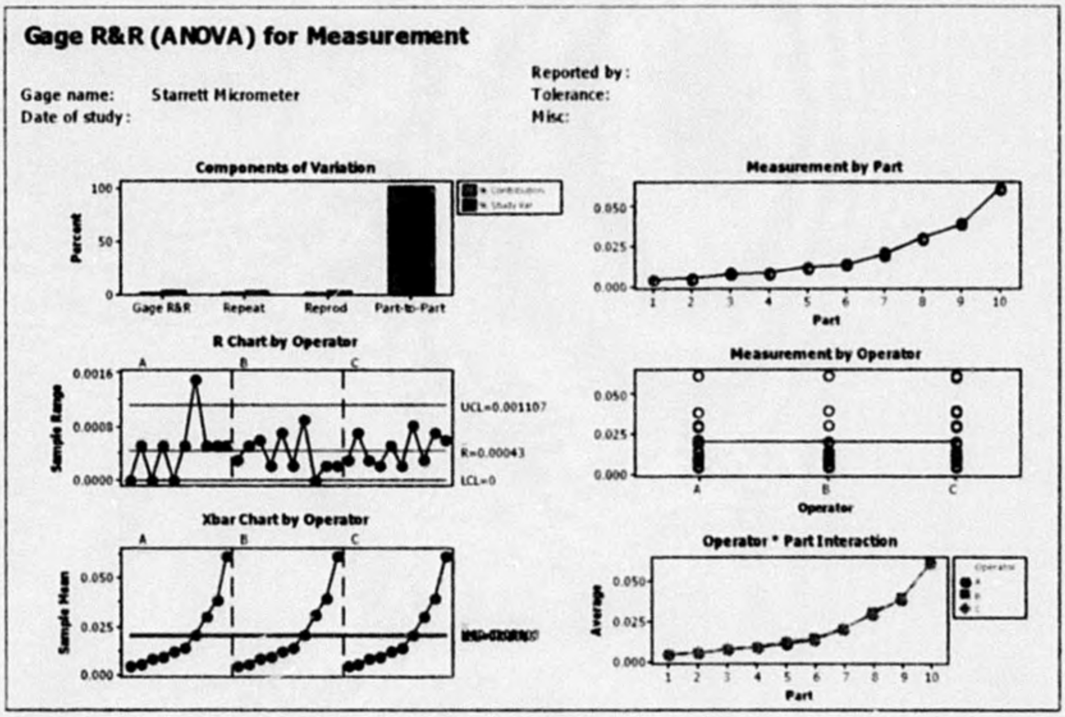
| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Part | 9 | 0.0272377 | 0.0030264 | 36775.8 | 0.000 |
| Operator | 2 | 0.0000017 | 0.0000009 | 10.4 | 0.000 |
| Repeatability | 78 | 0.0000064 | 0.0000001 | | |
| Total | 89 | 0.0272458 | | | |

**Gage R&R**

| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000001 | 0.03 |
| Repeatability | 0.0000001 | 0.02 |
| Reproducibility | 0.0000000 | 0.01 |
| Operator | 0.0000000 | 0.01 |
| Part-To-Part | 0.0003363 | 99.97 |
| Total Variation | 0.0003364 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) |
|---|---|---|---|
| Total Gage R&R | 0.0003286 | 0.001972 | 1.79 |
| Repeatability | 0.0002869 | 0.001721 | 1.56 |
| Reproducibility | 0.0001603 | 0.000962 | 0.87 |
| Operator | 0.0001603 | 0.000962 | 0.87 |
| Part-To-Part | 0.0183373 | 0.110024 | 99.98 |
| Total Variation | 0.0183403 | 0.110042 | 100.00 |

Number of Distinct Categories = 78

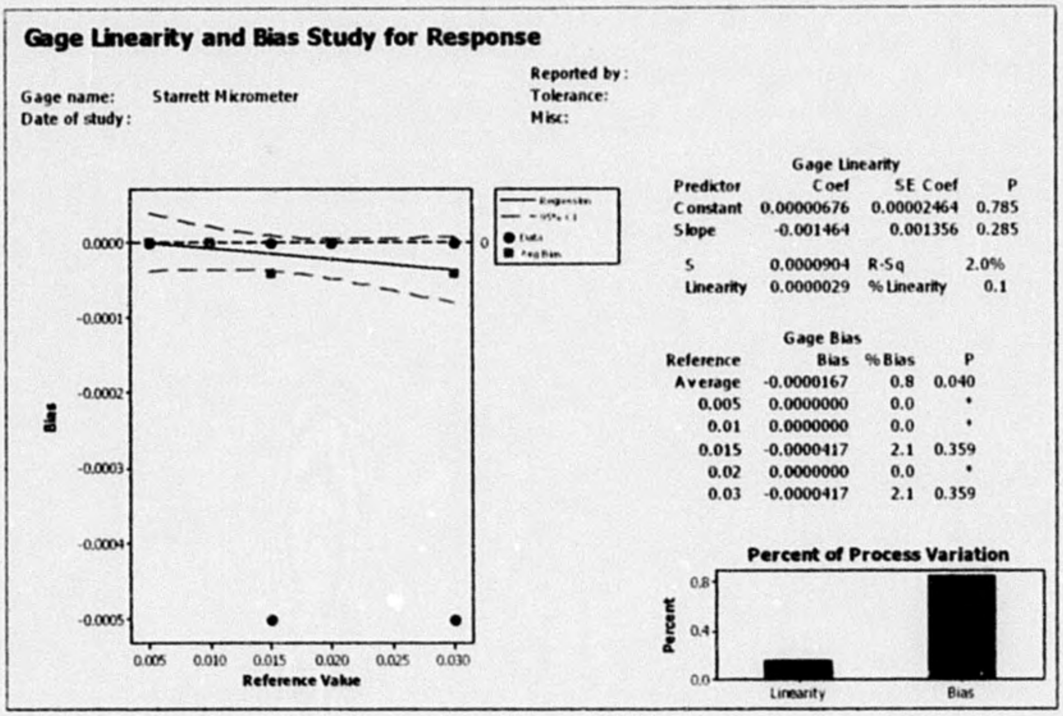



## Starret Micrometer – Linearity & Bias

| Part | Master | Response |
|---|---|---|
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |

| | | |
|---|---|---|
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 2 | 0.010 | 0.0100 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0145 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 3 | 0.015 | 0.0150 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 4 | 0.020 | 0.0200 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0295 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |

| | | |
|---|---|---|
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |

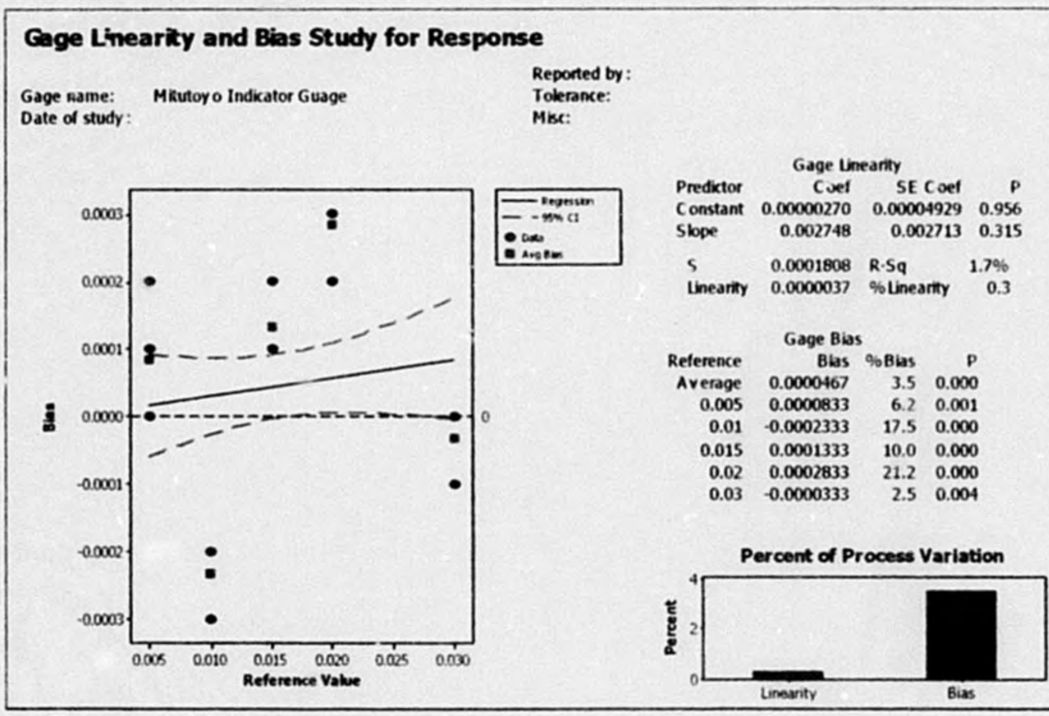



Mitutoyo Indicator - Gage Linearity & Bias

| Part | Master | Response |
|---|---|---|
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0052 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0051 |
| 1 | 0.005 | 0.0050 |

| | | |
|---|---|---|
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0097 |
| 2 | 0.010 | 0.0097 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0097 |
| 2 | 0.010 | 0.0097 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0098 |
| 2 | 0.010 | 0.0098 |
| 3 | 0.015 | 0.0152 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0152 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0152 |
| 3 | 0.015 | 0.0152 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0151 |
| 3 | 0.015 | 0.0151 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0202 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0202 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 4 | 0.020 | 0.0203 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0299 |
| 5 | 0.030 | 0.0300 |

| | | |
|---|---|---|
| 5 | 0.030 | 0.0299 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0299 |
| 5 | 0.030 | 0.0300 |
| 5 | 0.030 | 0.0299 |
| 5 | 0.030 | 0.0300 |

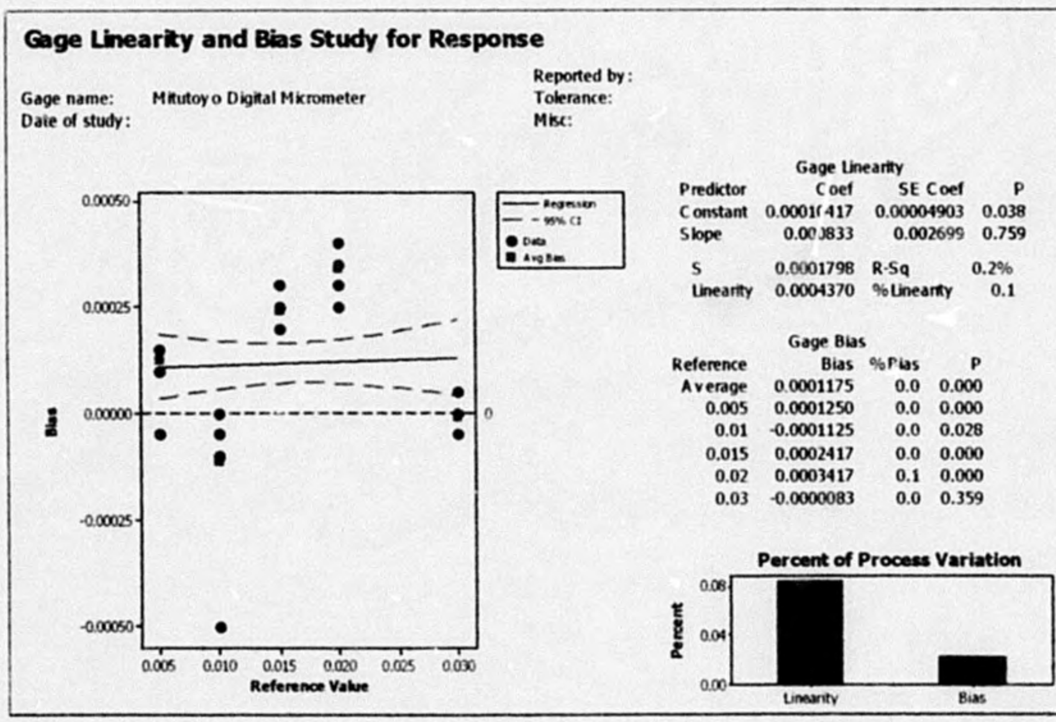



Digital Micrometer - Linearity & Bias

| Part | Master | Response |
|---|---|---|
| 1 | 0.005 | 0.00495 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |

| | | |
|---|---|---|
| 1 | 0.005 | 0.00510 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00515 |
| 1 | 0.005 | 0.00510 |
| 1 | 0.005 | 0.00515 |
| 2 | 0.010 | 0.00995 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.01000 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.00950 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.01000 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.00990 |
| 2 | 0.010 | 0.00990 |
| 3 | 0.015 | 0.01530 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01530 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |
| 4 | 0.020 | 0.02040 |
| 4 | 0.020 | 0.02040 |
| 4 | 0.020 | 0.02030 |
| 4 | 0.020 | 0.02030 |
| 4 | 0.020 | 0.02025 |
| 4 | 0.020 | 0.02030 |
| 4 | 0.020 | 0.02035 |
| 4 | 0.020 | 0.02035 |
| 4 | 0.020 | 0.02040 |

| | | |
|---|---|---|
| 4 | 0.020 | 0.02035 |
| 4 | 0.020 | 0.02035 |
| 4 | 0.020 | 0.02035 |
| 5 | 0.030 | 0.02995 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03005 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.02995 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.03000 |
| 5 | 0.030 | 0.02995 |

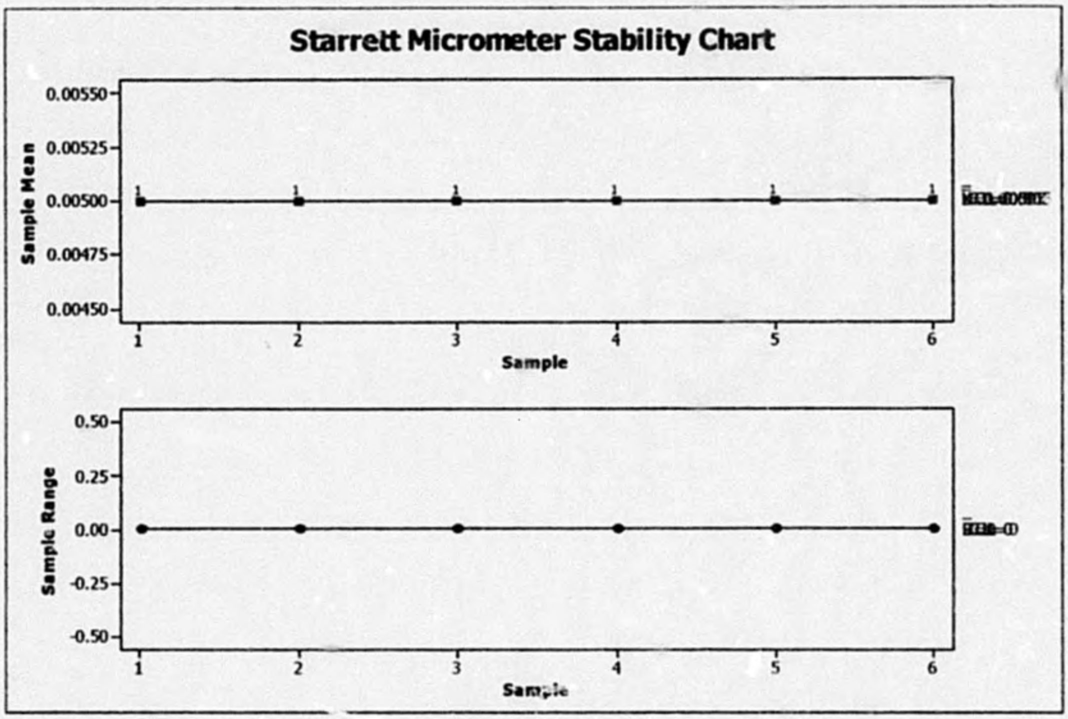


Starrett Micrometer
Gage Stability

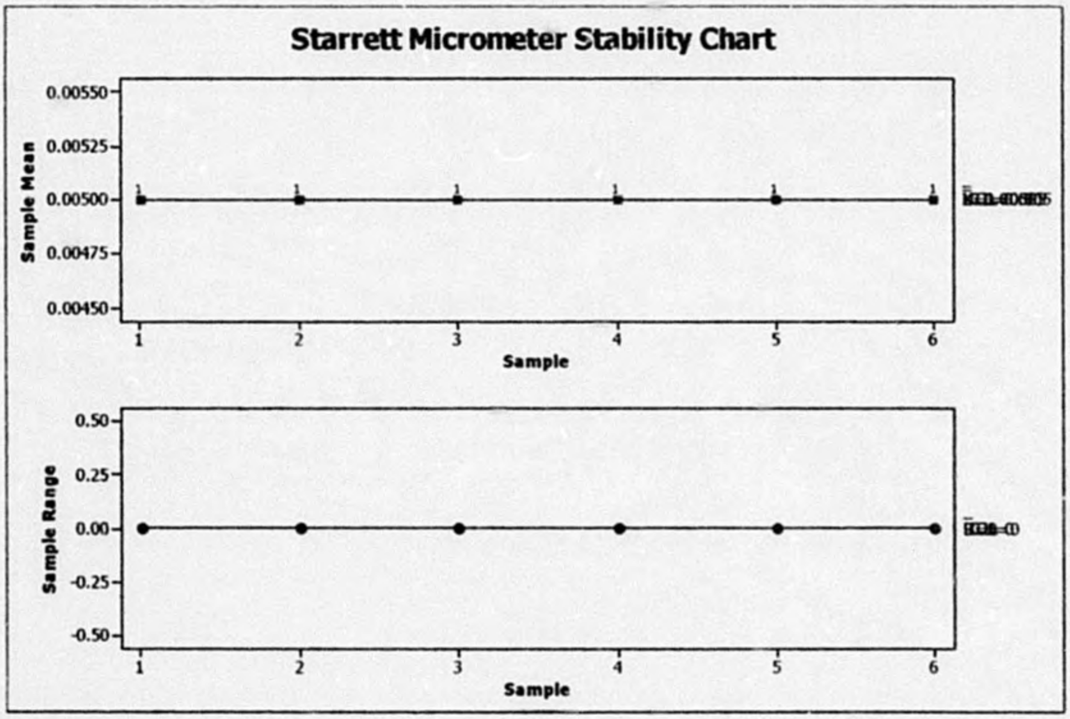
| Part | Operator | Measurement |
|---|---|---|
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |

Starrett Micrometer
Gage Stability

| Part | Operator | Measurement |
|---|---|---|
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |
| 1 | 0.005 | 0.0050 |



Starrett Micrometer Stability Chart
Sample Mean
0.00550
0.00525
0.00500
0.00475
0.00450
Sample
Sample Range
0.50
0.25
0.00
-0.25
-0.50
Sample

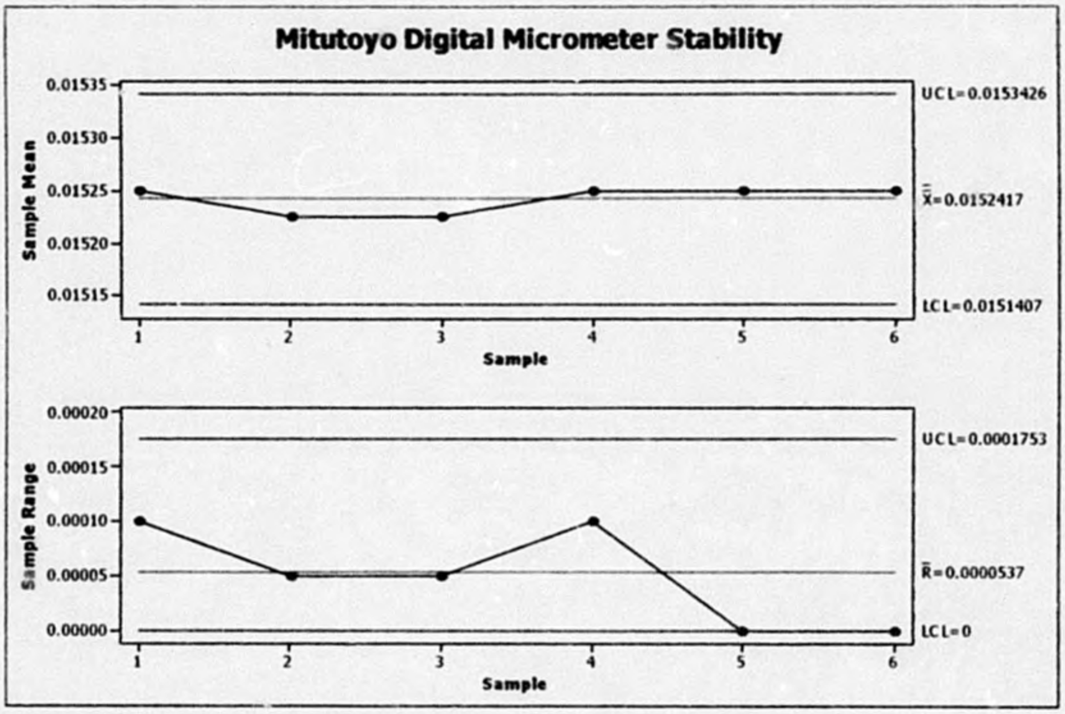
Starrett Micrometer Stability Chart
Sample Mean
0.00550
0.00525
0.00500
0.00475
0.00450
Sample
Sample Range
0.50
0.25
0.00
-0.25
-0.50
Sample

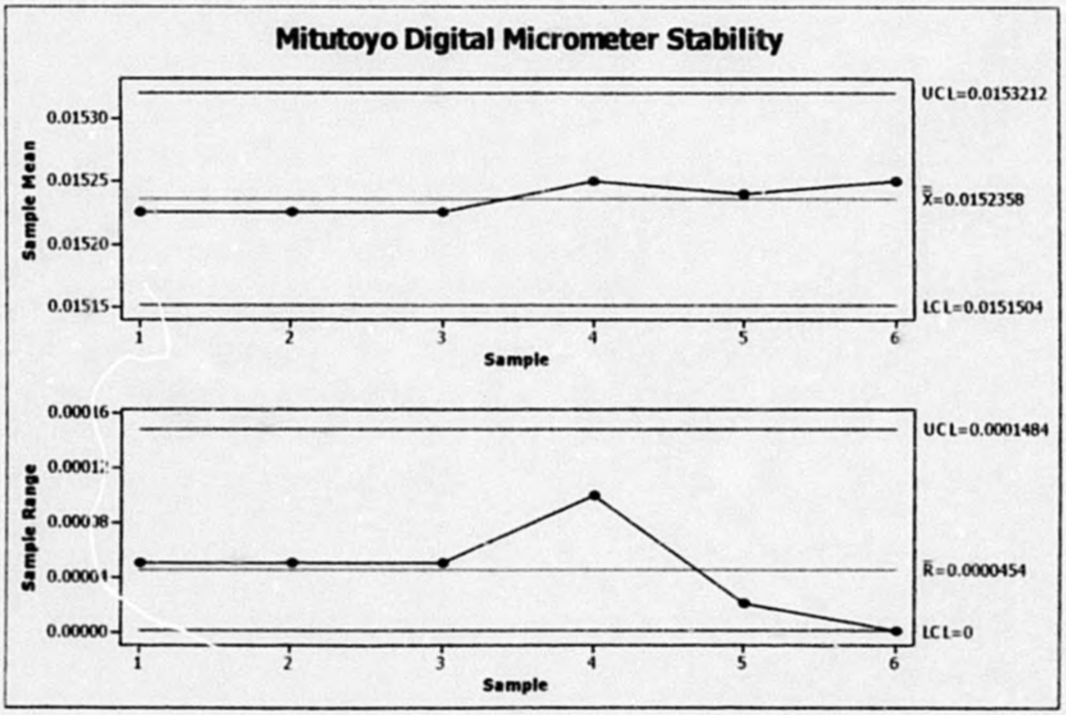
Mitutoyo Digital Micrometer
Gage Stability

| Part | Operator | Measurement |
|---|---|---|
| 3 | 0.015 | 0.01530 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01530 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |

Mitutoyo Digital Micrometer
Gage Stability

| Part | Operator | Measurement |
|---|---|---|
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01530 |
| 3 | 0.015 | 0.01520 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01523 |
| 3 | 0.015 | 0.01525 |
| 3 | 0.015 | 0.01525 |


Mitutoyo Digital Micrometer Stability
Sample Mean
Sample
UCL=0.0153426
X̿=0.0152417
LCL=0.0151407
Sample Range
UCL=0.0001753
R̄=0.0000537
LCL=0

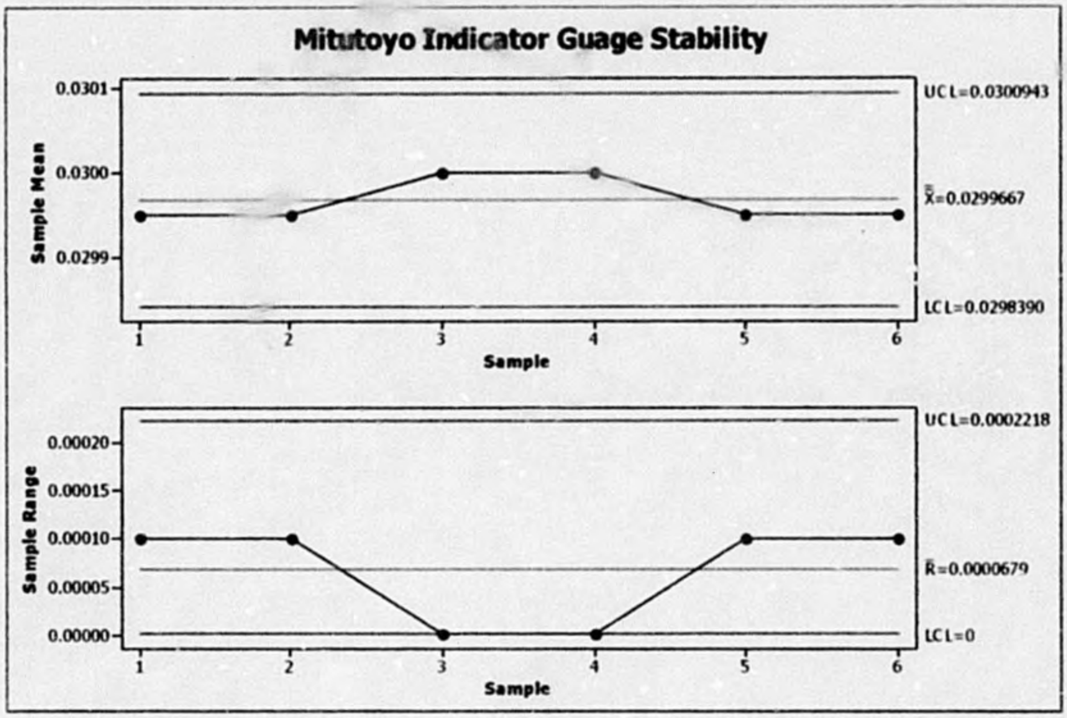

Mitutoyo Digital Micrometer Stability
Sample Mean
Sample
UCL=0.0153212
X̿=0.0152358
LCL=0.0151504
Sample Range
UCL=0.0001484
R̄=0.0000454
LCL=0

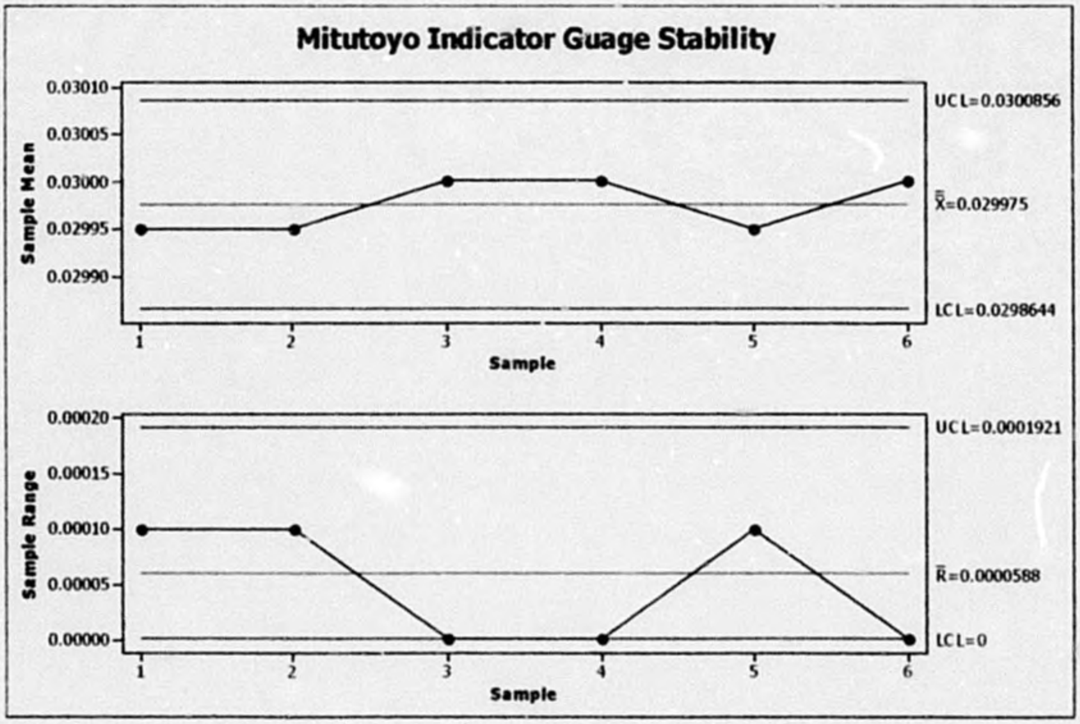
Mitutoyo Indicator Guage
Gage Stability

| Part | Operator | Measurement |
| --- | --- | --- |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |

Mitutoyo Indicator Guage
Gage Stability

| Part | Operator | Measurement |
| --- | --- | --- |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0299 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |
| 5 | 0.03 | 0.0300 |


Mitutoyo Indicator Guage Stability
Sample Mean
0.0301
0.0300
0.0299
UCL=0.0300943
X̿=0.0299667
LCL=0.0298390
Sample
Sample Range
0.00020
0.00015
0.00010
0.00005
0.00000
UCL=0.0002218
R̄=0.0000679
LCL=0
Sample


Mitutoyo Indicator Guage Stability
Sample Mean
0.03010
0.03005
0.03000
0.02995
0.02990
UCL=0.0300856
X̿=0.029975
LCL=0.0298644
Sample
Sample Range
0.00020
0.00015
0.00010
0.00005
0.00000
UCL=0.0001921
R̄=0.0000588
LCL=0
Sample